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TECHNOLOGIC PAPERS
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BUREAU OF STANDARDS

S. W. STRATTON, DIRECTOR

No. 80

CONSTITUTION AND MICROSTRUCTURE OF PORCELAIN

BY

A. A. KLEIN, Assistant Physicist
Bureau of Standards

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By A. A. Klein, Assistant Physicist

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I. INTRODUCTION

The question of the microstructure and constitution of bodies consisting of mixtures of feldspar, quartz, and clay substance is, indeed, an interesting one both scientifically and technically. Feldspar, quartz, and clay (kaolin and ball clay) are the raw materials which enter into the manufacture of white ware (porous non-vitreous) bodies as well as in the manufacture of porcelain and allied (dense, vitreous) ware. The physical and chemical changes affecting these materials which take place at temperatures in the vicinity of those employed in the burning of commercial ware are of interest scientifically. These can be studied by the microscopical examination of the burned product. Furthermore, the ability to determine by means of microscopic methods the approximate composition of a body and above all the temperature range at which the body has been burned would be of great technical importance. Within limits, all this data can be determined by petrographic microscopical means. This method of investigation gives much information that can not be determined by purely chemical means and ought to become an important tool in the hands of the ceramic investigator as well as the technical ceramist.

II. LITERATURE

The literature on this subject is voluminous. The first investigators of the constitution of porcelain were Brongiart and Malaguti.[1] They observed that a mixture of chemically pure silica, alumina, lime (carbonate), and potash (as carbonate) in the proportions by weight which were obtained by the analysis of Sèvres porcelain gave a more fusible mass than when the oxides were originally in chemical combination with each other. Von Bischof [2] showed that the chemical constitution of the raw materials was of importance in the formation of porcelain. According to G. Rose,[3] porcelain is either a mixture of feldspar glass and kaolin or what he considered more probable, the feldspar and kaolin are, either wholly or partially, in chemical combination. According to the microscopic investigation of Behrens [4] the kaolin is more soluble in the molten feldspar than the quartz in the formation of porcelain. The quartz partly retains its original crystalline condition while the kaolin exists entirely in the melt. When porcelains containing quartz are burned most of the quartz splinters become rounded through solution and are covered with a silicate zone which protects the quartz from further solution, especially since the groundmass is not sufficiently fluid for a diffusion of the different silicates. According to Behrens the groundmass of a porcelain undergoes devitrification. The material separating from the glass is dissolved more slowly in hydrofluoric acid than the quartz and glass. Seger[5] reaches the following conclusions in his investigations on the changes involved in the burning of porcelain. "One or more constituents melt and have a solvent effect on the rest of the constituents. The undissolved portion forms a solid skeleton which holds together the form of the mass. At higher temperatures solution proceeds and the pores of the mass are more or less filled with the liquid phase, until finally the pores are completely filled and closed." Seger deduced also that the influence of the feldspar on the kaolin is less than on the quartz. The microscopic studies of Hussak,[6] who examined thin sections of several porcelains burned at different temperatures, are of interest. According to him a thin section of a very low-burned specimen showed no change in the mixture, all the constituents being doubly refracting and clearly distinguishable from each other. With an increase in burning temperature the feldspar begins to melt and the formation of glass begins; the quartz is sharp grained; the amount of kaolin is, however, apparently smaller. With increased heating the feldspar for the most part melts, and the quartz likewise goes into solution. With a further increase in burning temperature a still smaller amount of feldspar and only the larger quartz grains are observed in a colorless groundmass. With high magnifications a network of long, thin, weakly doubly refracting needles can be observed. Another burning affects the constituents but little, there being more glass and gas bubbles present. According to Hussak, therefore, porcelain consists of an amorphous groundmass with a few large quartz grains, a few large gas bubbles, and fine needles resembling sillimanite, $Al_2O_3.SiO_2$.

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[1] Pogg. Ann., p. 89; 1843.

[2] Notizbl, p. 162; 1875.

[3] Pogg. Ann., **66**, p. 97; 1845.

[4] Pogg. Ann., **150**, p. 386; 1873.

Vernadsky[7] heated refractory clay at white heat for 72 hours and observed small prismatic crystallites. These were optically positive, showed an extinction parallel to the prismatic axis, and were not soluble in cold concentrated hydrofluoric acid. He observed similar but better developed crystallites by heating a mixture of alumina and silica in the molecular ratio of 1:2 to about 1400°.

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[5] Tonind, Zeit., p. 272; 1876. [6] Sprechsaal, p. 153; 1889. [7] Bull. de la Soc. fr. de Min., 13, p. 256; 1890.

The needles often lay around unmolten alumina or silica. Isolated crystals analyzed 37.31 per cent SiO_2 and 63.65 per cent Al_2O_3 which agrees closely with the theoretical analytical figures for $Al_2O_3.SiO_2$, viz, 37.02 per cent SiO_2 and 62.98 per cent Al_2O_3. Vernadsky also found that the two other modifications of $Al_2O_3.SiO_2$, cyanite and andalusite, changed to sillimanite at 1320° to 1380°. The latter has also been observed by other investigators.

Mellor [8] observed crystallized sillimanite in Chinese and Berlin porcelain and held the same views concerning its formation as Vernadsky.

Glasenapp [9] came to the following conclusions as a result of his microscopic studies: All clays dissociate at a sufficiently high temperature into a glassy groundmass and a crystalline portion. Their dissociation increases with increasing temperature and with the duration of burning. He believed that the glassy groundmass was richer in silica and that the crystalline material was higher in alumina.

Plenske [10] has investigated the microstructure and formation of porcelain. He divides porcelains microscopically as follows:

I. Porcelain without crystallites in which he notes quartz grains of 2 to 30 μ in diameter with sharp edges and faces, very little being dissolved. Kaolin has lost its crystal outline but occurs as an aggregate of curled up amorphous grains 2 to 6 μ in diameter. Gas bubbles are also noted.

II. Porcelain with very few isolated crystallites, which he notes in a glassy groundmass, amorphous $Al_2O_3.2SiO_2$, quartz, bubbles and prism crystallites showing double refraction, parallel extinction, and positive optical character. They may attain 20 μ in length. Only a small quantity of quartz is dissolved.

III. Porcelain with larger groups of crystals consisting of a glassy groundmass, with large groups of crystallites, cloudy amorphous $Al_2O_3.2SiO_2$, quartz more or less corroded, with a zone of glass rich in silica. The crystallites occur irregularly, also grouped in parallel order and sometimes they show lattice structure.

IV. Porcelain with larger groups of crystallites. This type shows an equal distribution of many crystallites in a glassy groundmass. The quartz varies greatly in amount and is more or less corroded. Amorphous $Al_2O_3.2SiO_2$ is observed. According to

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[8] J. Soc. Chem. Ind., **26**, p. 375; 1907.

[9] Tonind. Ztg., **31**, p. 1167; 1907.

[10] Sprechsaal, **41**, nos. 20, 21, 22, 1908; Tonind. Zeit., **32**, pp. 1343–1345. 1908.

Plenske, the vitrification of porcelain proceeds as follows: The feldspar on fusion dissolves the kaolin and quartz, but more of the former than of the latter. The large quartz grains are dissolved at the edges. On cooling, the crystals of sillimanite are formed by devitrification, while in places where all the quartz is dissolved, glass is noted as the result of cooling. Kaolin burned in the high glost fire appears amorphous with but few crystals, due to the fluxing action of impurities. In kaolin-quartz bodies no mutual chemical reaction takes place. Quartz-feldspar mixtures show mutual solution. Kaolin-feldspar mixtures show amorphous $Al_2O_2.SiO_2$ in cloudy form deposited in the feldspar glass, a phenomenon observed in porcelain. In part, solution has taken place with subsequent crystallization of sillimanite. The crystals of sillimanite appear only with a content of 50 per cent clay substance and are best developed in 75 per cent clay substance and 25 25 per cent feldspar. With a ratio of 1 clay to 3 feldspar no devitrification takes place. The longer and higher the burn the greater is the number of crystals formed, excepting in those bodies high in feldspar burned at cone 9 or below. Porcelain thus appears to be hypocrystalline and porphyritic, consisting of a glassy groundmass, amorphous $Al_2O_3.2SiO_2$, corroded crystals of quartz, sillimanite and cavities, or bubbles.

A. Zoellner[11] made a painstaking study of porcelain. His work consisted in the preparation of porcelain bodies, their microscopic study, and the separation of the crystalline portion by means of dilute hydrofluoric acid (30 to 35 per cent). He found that feldspar at the temperature of the porcelain kiln may dissolve 3.5 per cent alumina, 14 per cent clay substance, and 60 to 70 per cent quartz. These relations are not changed in the presence of more than two components. Hard porcelain consists of a glassy groundmass filled with numerous needle-like crystals, corroded quartz, and many air bubbles. The crystals agree optically with sillimanite. Porcelain burned at a temperature lower than cone 12 shows fused feldspar, partially attacked quartz, and an amorphous silicate, probably dehydrated clay substance. The analysis of the residue from Seger porcelain and two other porcelains, isolated with hydrofluoric acid, showed its molecular raito of $SiO_2 : Al_2O_3$ to be 1 : 1, confirming the optical evidence of the presence of sillimanite. All the sillimanite is derived from the kaolin or clay substance and is not due to devitrification (as

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[11] Sprechsaal, 41, pp. 471–473 and 533–536.

Plenske held), but to a molecular change of the clay substance, an action which is accelerated by the presence of fluxes. Clay substance is thus split up into an amorphous, glassy silicate higher in silica and into the crystalline silicate higher in alumina, sillimanite. Optical or chemical examination offers a means of distinguishing between hard-burned and soft-burned porcelain, the formation of sillimanite being the criterion.

Watts[12] comes to the following conclusions:

A hard feldspar will do no more than bond the other constituents at temperatures lower than cone 9. The clay substance is first dissolved in the feldspar glass and later the flint particles begin to be dissolved, until at cone 10 the porcelain begins to show evidence of sillimanite crystallization. At cone 13 a hard feldspar becomes completely fused and fluid, permitting such crystallization as conditions and other ingredients will allow.

III. PRESENT INVESTIGATION

In order to obtain as much information as possible on the constitution and miscrostructure of porcelain, it was decided to investigate the changes involved in each of the raw materials by burning at various known temperatures, in systems consisting of two of the raw materials, and in what might be classed as a ternary system of the three raw materials, feldspar, quartz, and clay substance. Furthermore, it was proposed to examine commercial specimens representing the technical practice in various countries.

Both the method of immersed grains and that of thin sections were used in the petrographic examinations. The latter method is too well known for extensive comment, and it suffices here to state that the thin sections were ground, prepared, and mounted in the usual manner. This method was used only for photography and as an adjunct to the method of immersed grains to furnish data on the structural relationship of the constituents; but even here it was limited in the scope of its applicability, owing to the extreme minuteness and intergrown character of some of the constituents.

For the determination of the physical and chemical changes taking place in the burning of the specimens and to obtain reliable data concerning their constitution, the method of immersed grains was employed. It furnished information to some extent regarding structural relations, especially where observations had to be made with high magnifications on poorly developed material. The method consisted of detaching a small piece of the specimen to be examined, tapping it to a powder of the desired fineness and immersing portions of the powder in liquids of known indices of refraction. The advantages of this method over that of thin sections in the study of artificial silicates has been repeatedly shown by the Geophysical Laboratory in their researches and by our laboratory in the studies on the constitution and hydration of Portland cement.

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[12] Trans. Am. Cer. Soc., **11**, pp. 185–201; 1909.

A. FELDSPAR

The melting points and thermal relations of the feldspars have been thoroughly investigated. Orthoclase and microcline are used almost exclusively in the production of porcelain, although some of the plagioclases may occur as impurities in the feldspar raw material. According to many investigators, orthoclase melts below 1200° to an apparently solid isotropic phase. The melting interval is not sharp but extends through quite a range of time. As the temperature is raised above the melting point, the viscosity of the isotropic phase is lowered and eventually at about 1300° the isotropic phase forms a thick viscous liquid which is extremely resistant to devitrification.

The plagioclases form a complete isomorphous series with albite and anorthite as end members. According to Bowen [13] albite melts at 1100° ± 10° and anorthite at 1550° ± 2°. He has also determined the solidus and liquidus temperatures for all the intermediate concentrations, and the curves representing these temperatures are typical for completely isomorphous series.

B. SILICA

Concerning the thermal properties of silica, Fenner [14] reports the following:

α quartz (stable at ordinary temperatures) inverts to β quartz at 575°. At 870° ± 10° with the aid of sodium tungstate as a flux, β quartz inverts to β_2 tridymite, and with the same flux at 1470° ± 10° β_2 tridymite inverts to β cristobalite which melts at 1625°. With an absence of mineralizer and with fairly rapid cooling, β cristobalite does not revert to β_2 tridymite, nor does β_2 tridymite revert to β quartz. β cristobalite reverts readily to α cristobalite at about 180°–270° and β_2 tridymite reverts likewise to β_1 tridymite at 163°. The latter compound reverts to α tridymite at 117°. Time is a great factor in the quartz-tridymite and tridymite-cristobalite inversions. It is easily possible to heat quartz rapidly enough so that it will invert above 1400° at once to cristobalite with probably only a small quantity of tridymite. With the thermal behavior of feldspar and quartz well established, it was thought unadvisable to go over this ground again.

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[13] Z. Anorg. Chem., 82, pp. 283–307; Am. J. Sci., 35, pp. 577–599, 1913.

[14] J. Wash. Acad. Sci., II, p. 20, 1912; Am. J. Sci., 36, pp. 331–384, 1913.

C. KAOLIN

Kaolin is an inclusive term applied to compounds of the general type $Al_2O_3.2SiO_2.2H_2O$ (kaolinite). Some of the white burning clays approach the composition of pure kaolin very closely.

Kaolin is a material concerning whose behavior on heating many and varied opinions have been held. It is known, for example, that the combined water is lost within a certain temperature range. Le Chatelier, Hillebrand, F. W. Clarke, McNeil, Knote, Ashley, Mellor and Holdcroft, Rieke, and others have found different endothermic ranges. Perhaps the most authoritative investigation of this problem is that of Brown and Montgomery.[15] They found that the combined water is expelled at comparatively low temperatures, so that even at 450° the bulk of it may be driven off. In heating clay to constancy of weight at different temperatures, the velocity of the dehydrating reaction is very slow at first and becomes suddenly rapid at 500°. The remaining portion of the water is removed more slowly so that a temperature of not less than 800° is required to accomplish complete expulsion.

Furthermore, an exothermic energy change was noted at about 925° by Le Chatelier and by Ashley,[16] and at about 900° by Mellor and Holdcroft.[17] From a study of the hygroscopicity, specific gravity, and solubilities in hydrochloric acid of clays heated to 600° to 700°, Mellor and Holdcroft concluded that above 500° kaolin dissociates into free alumina, free silica, and water. The exothermic change noted may be a physical change of the alumina. The formation of sillimanite at higher temperatures is then due to a recombination of a part of the free silica with alumina.

Sokoloff [18] from his study of the solubility in hydrochloric acid of clays heated to various temperatures, reached conclusions similar to those of Mellor and Holdcroft.

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[15] Bureau of Standards Tech. Paper No. 21, 1913.

[16] J. Ind. Eng. Chem., 3, pp. 91–95, 1910.

[17] Trans. Eng. Ceram. Soc., 10, pp. 94–120.

[18] Tonind. Zeit., 36, pp. 1107–1111.

In the present investigation two fairly pure kaolins were used, a washed North Carolina kaolin and an English kaolin. The chemical analyses were as follows:

	North Carolina	English		North Carolina	English
	Per cent	Per cent		Per cent	Per cent
SiO_2	45.80	47.68	MgO	0.11	0.46
Al_2O_3	38.65	37.73	Na_2O	.05	.06
Fe_2O_3	.91	.70	K_2O	.23	.67
CaO	.26	.16	H_2O	14.00	12.55

The microscopic examination of the North Carolina kaolin showed that the chief constituent was a kaolinitic material which occurred in extremely small flaky grains. These grains appeared mainly amorphous, although a low order gray interference color was observed on a few. Due, however, to the low birefringence and the minuteness of the grains, interference figures could not be obtained. The index of refraction was, however, about 1.55. In addition were noted quite a quantity of sericite, a smaller amount of fine-grained quartz, and an extremely small amount of biotite in greenish brown flakes.

Kaolinitic material was the chief constituent of the English kaolin. It was noted in very fine flaky grains which, however, were larger than those of the North Carolina kaolin, and showed more of a tendency toward anisotropy. Indistinct biaxial negative interference figures were obtained, and the mean index of refraction was found to be 1.55. Sericitic mica was observed in a larger amount than in the North Carolina material, but no biotite was noted. A small amount of quartz was observed, which was coarser grained than the other constituents.

Both of these kaolins were heated in a platinum resistance furnace for five hours at 600° and for two hours at each of the following temperatures: 900°, 1100°, 1200°, 1300°, 1400°, 1450°, and 1500°. A microscopic examination was made of each of the burns.

The examination of these specimens revealed the following facts: As soon as the water of combination was driven off, the kaolinitic material became entirely isotropic, but the index of refraction altered to only a slight extent. Then there was no profound change noted in the optical properties until the temperature of burning reached upward of 1200°. At this point there was noted a beginning of an incipient dissociation of the kaolinitic material which became manifest by the formation in very small amounts of two isotropic substances, one of which had an index lower than 1.50 and the other had an index higher than 1.60. They were extremely intergrown and showed no attempt toward crystal form.

The dissociation remained incipient until a burning temperature of 1400° was reached, when a complete dissociation occurred and the two isotropic compounds noted above were formed. The higher refracting isotropic material showed no crystalline development, but occurred as extremely minute, almost submicroscopic, irregular to rounded grains intimately intergrown with the lower refracting product of dissociation. The effect was such that due to reflection and refraction of light passing through them these grains of dissociated kaolin appeared cloudy and brownish in color. In addition there were noted a few aggregates of minute thin prismatic crystals. These were apparently isotropic, being too thin to show distinct interference, and the index of refraction, which could not be obtained accurately, was greater than 1.60.

Between 1400° and 1450° nearly all the minute isotropic higher refracting grains assumed a prismatic development. Most of these minute needle crystallites were so thin as to be apparently isotropic, and their length was not over 0.01 mm. For the most part they exhibited no regular orientation, but occasionally they showed parallel grouping and sometimes these parallel grouped aggregates intersected each other at an angle of 60°, giving rise to a lattice structure. Occasionally an aggregate of these needles showed a first order gray to white interference color. The extinction was then noted parallel to the prism axis, and the character of the principal zone was positive. The index of refraction was about 1.64. Interference figures, although not often obtained, were biaxial and the optical character was positive. The plane of the optic axis was parallel to the prism axis. These optical properties agree with those given for the mineral sillimanite, $Al_2O_3.SiO_3$.

The evidence points to the fact that these needle crystals result directly from the crystallization of the amorphous higher refracting compound noted in specimens burned at 1400°, since, firstly, the latter disappear with the formation of the needle crystallites, and secondly, in the specimens burned at 1450° a slight amount of amorphous high refracting material was noted, from which minute needle crystals extended, showing this crystallization in an incipient state. It therefore seems certain that this amorphous material is no more nor less than an amorphous phase of sillimanite, and its formation results from the dissociation of the kaolin molecule before there is sufficient mobility for molecular orientation in any definite crystalline form.

D. FELDSPAR-QUARTZ SERIES

The feldspar used was a Maine feldspar with the following analysis:

	Per cent.
SiO_2	69.56
Al_2O_3	17.36
Fe_2O_3	.30
CaO	.22
MgO	.12
Na_2O	3.64
K_2O	6.90
	98.10

It consisted for the most part of orthoclase with a small amount of plagioclase having a composition about that of albite oligoclase. In addition, quartz and muscovite and microcline were noted in approximately equal amounts. A quantitative microscopical determination of the quartz and muscovite gave a value of 10 per cent, indicating the presence of about 5 per cent quartz and 5 per cent mica.

The following mixtures (see Fig. 1) were prepared and burned at 1340° and at 1460°:

Mark	Feldspar	Quartz	Mark	Feldspar	Quartz
	Per cent	Per cent		Per cent	Per cent
F-5	95	5	F-30	70	30
F-10	90	10	F-35	65	35
F-15	85	15	F-40	60	40
F-20	80	20	F-45	55	45
F-25	75	25	F-50	50	50

The mixtures made up to the above percentages were each placed in a refractory unglazed chemical porcelain crucible and heated in a large down-draft, gas-fired kiln, using compressed air. The total time consumed in making a run was about 24 hours, and the kiln was kept at the desired temperature for 2 to 3 hours.

F–5 (1340°).—The microscopic examination revealed the fact that the feldspar melted entirely to a glass and that the quartz was present as irregular grains showing more or less angularity and but a small amount of solution in the feldspar glass as was evidenced by a slight rounding of the corners and edges of the smaller grains. Quantitative microscopical determinations of the amount of undissolved quartz present gave an average of about 9 per cent. Since about 5 per cent quartz was present originally in the feldspar and 5 per cent was added, it can be seen that only a small amount of solution took place.

F–10 (1340°).—This specimen showed exactly the same structure as F–5, but for the increased amount of quartz. Grains of the latter showed but little rounding and the quantitative microscopic determinations indicated that about 15 per cent was present.

F–15 to F–50 (1340°).—These specimens resembled each other as well as F–5 and F–10 in constitution and structure. They differed from each other in the increasing quartz content and the correspondingly decreasing feldspar glass content. In all cases the amount of quartz dissolved was small, and only the smaller grains showed slight but appreciable rounding due to solution. (See Figs. 2, 3, 4, and 5.) The quantitative determinations of quartz present affirmed the statement that the solubility of the quartz at this temperature is comparatively small. F–40 which originally contained about 43 per cent quartz gave an average of about 40 per cent present. Likewise F–45, whose quartz content must originally have been about 48 per cent, gave an average of about 45 per cent present.

F–5, etc. (1460°).—The quartz dissolved in the feldspar glass in all the specimens except F–40, F–45, and F–50. In these specimens there was a trace of quartz left which was noted in very small round grains. (See Fig. 6.) For all practical purposes it may be said that quartz dissolves in a feldspar melt at 1460° at least to the concentration of 50 per cent quartz to 50 per cent feldspar.

E. FELDSPAR-KAOLIN SERIES

The same Maine feldspar was used in this series as was used in the feldspar-quartz series. The kaolin was the washed North Carolina kaolin described previously.

The following mixtures (see Fig. 1) were prepared and burned at 1340° and at 1460°.

Mark	Feldspar	Kaolin	Mark	Feldspar	Kaolin
	Per cent	Per cent		Per cent	Per cent
C–5	95	5	C–30	70	30
C–10	90	10	C–35	65	35
C–15	85	15	C–40	60	40
C–20	80	20	C–45	55	45
C–25	75	25	C–50	50	50

The data on burning is identical with the data given on the burning of the feldspar-quartz series.

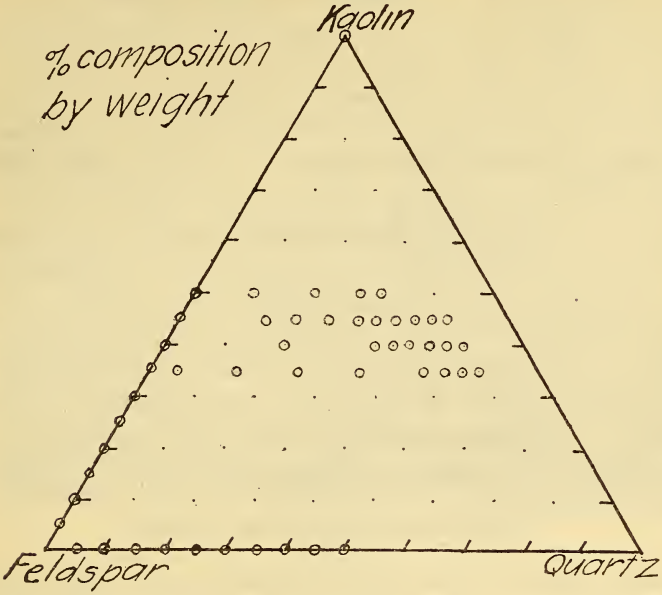

FIG. 1.—*Ternary diagram showing the compositions of the laboratory-prepared bodies examined.*

C–5 (1340°).—In this specimen the feldspar melted entirely to a glass containing inclusions of quartz, which was introduced as an impurity in the feldspar and kaolin raw materials, and aluminum silicate. The quartz inclusions showed but little solution, as indicated by a slight rounding of the sharp corners of the small grains, whereas the larger grains were angular. There appeared to be no profound difference in the refractive index between the glass adjacent to the quartz grains and the glass at a distance from them.

The original kaolinitic material dissociated entirely into silica and aluminum silicate. The former lost its entire identity in the feldspar melt, whereas the latter was observed in apparently isotropic aggregates of almost submicroscopic individuals whose index (greater than 1.60) was much higher than that of the glass. If crystallization had taken place at all, the prismatic crystallites were less than 0.002 mm in greatest dimension.

C–10, etc. (1340°).—In all the specimens of the series the feldspar melted, and quartz dissolved in the feldspar glass to only a small degree. The kaolinitic material, however, differs somewhat in the various specimens. In C–10 the condition of the aluminum silicate was the same as in C–5; it was apparently amorphous sillimanite. (See Fig. 7.) In C–15 a few sillimanite needle crystallites were observed and the amount increased as the kaolin content increased, at least up to the kaolin concentration of C–50.

C–5 (1460°).—Microscopically this specimen consisted of a homogeneous isotropic glass, showing neither quartz, amorphous sillimanite, nor sillimanite crystallites. Of particular interest was the complete solution in the feldspar glass of the small amount of aluminum silicate present at 1340°.

C–10, etc. (1460°).—In these specimens the quartz had practically all dissolved, since at most only a trace of minute rounded grains was observed. Sillimanite needles (see Fig. 8) occurred in all the specimens in increasing amounts as the kaolin content increased. The needles were perfectly developed and were comparatively large. For the most part they possessed no definite orientation, although occasionally the parallel grouping and the lattice structure described previously were noted.

F. FELDSPAR-QUARTZ-CLAY BODIES

1. FIRST SERIES (HIGH QUARTZ, LOW FELDSPAR).—The specimens of this series were prepared by Bleininger and Teetor in their study on the viscosity of porcelain bodies.[19] The data on their composition and burning will be given here but briefly, since it may be found in full detail in the report of their work.

The compositions are indicated in Table 2 and Fig. 1. These must be regarded as approximate only, since they do not represent the analyses of the burned specimens, but are calculated from the analyses of the raw materials given in Table 1. It may be noted that these bodies are comparatively high in quartz content and low in that of feldspar. Some, in fact, simulate the composition of typical whiteware bodies. The clay used was a mixture of five parts of North Carolina kaolin, one part Georgia kaolin, and one part Tennessee ball clay. The firing of all the specimens for the viscosity investigation was carried to the following temperatures: 1065°, 1100°, 1125°, 1160°, 1190°, 1220°, 1250°, 1280°, 1310°, so that each specimen examined microscopically was subjected to nine different burnings between 1065° and 1310°. Furthermore, these specimens after having been examined were reburned at 1400° for observation concerning the changes involved between 1310° and 1400°.

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[19] Bureau of Standards Techn. Paper No. 30; 1914.

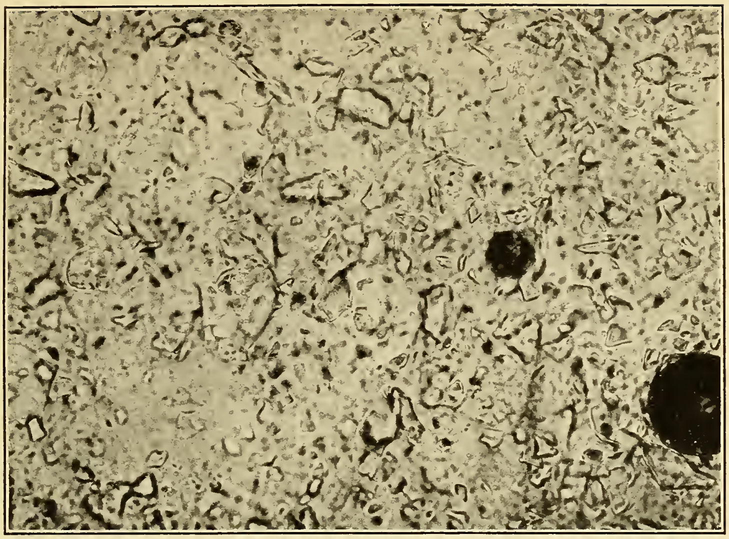

FIG. 2.—*Showing the body containing 90 per cent feldspar and 10 per cent quartz burned at 1340°. Note the evidence of only a small amount of solution of the quartz in the feldspar glass. This photograph was taken in ordinary light. Magnification=300 diameters*

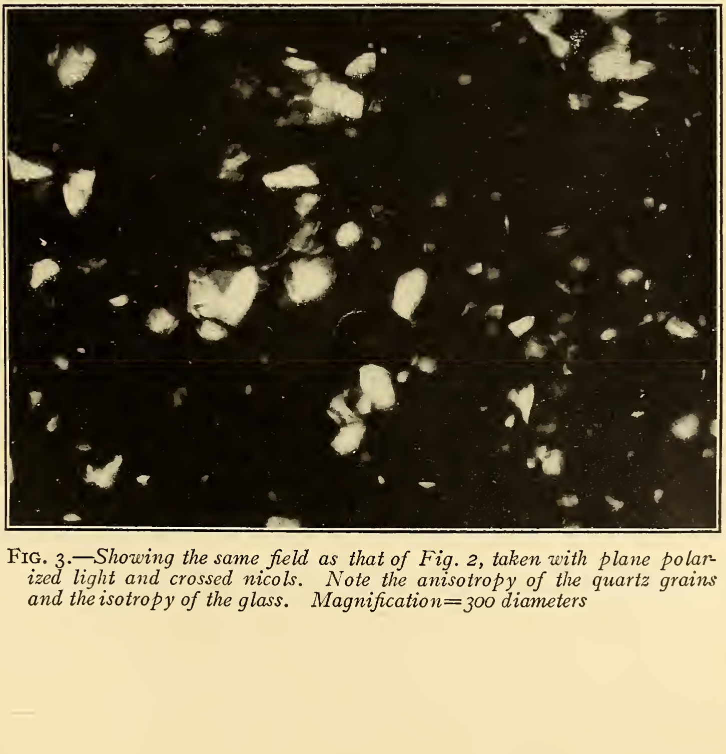

FIG. 3.—*Showing the same field as that of Fig. 2, taken with plane polarized light and crossed nicols. Note the anisotropy of the quartz grains and the isotropy of the glass. Magnification=300 diameters*

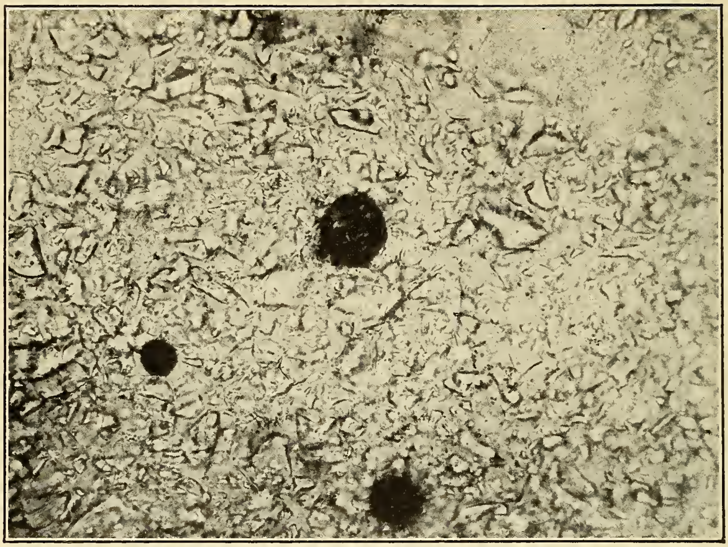

FIG. 4.—*Showing the body containing 55 per cent feldspar and 45 per cent quartz burned at 1340°. Note the small amount of quartz solution as evidenced by the incipient rounding of the quartz grains. Magnification=300 diameters*

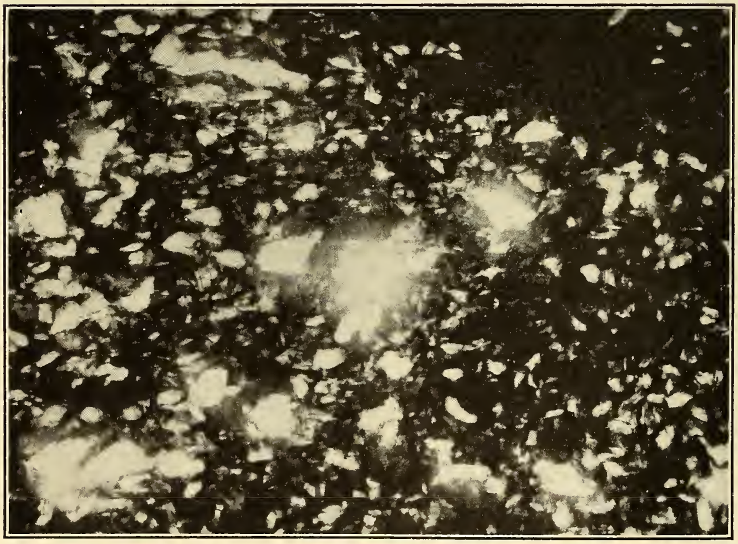

FIG. 5.—*Showing the same field as that of Fig. 4, taken with plane polarized light and crossed nicols. This photograph serves to contrast the doubly refracting quartz with the isotropic glass. Magnification=300 diameters*

A glance at Table 2 will indicate that series I consists of 4 subseries. In each subseries the kaolin content has been kept constant and the feldspar varied with the quartz. Thus the subseries are as follows: 35 per cent clay, 10 to 19 per cent feldspar, and 55 to 46 per cent quartz; 40 per cent clay, 10 to 25 per cent feldspar, and 50 to 35 per cent quartz; 45 per cent clay, 10 to 25 per cent feldspar, and 45 to 30 per cent quartz; 50 per cent clay, 19 to 22 per cent feldspar; 31 to 28 per cent quartz. The microscopical observations will be given collectively for each subseries.

Specimens 1 to 4 (1310°).—In general these specimens closely resembled each other in the changes undergone by the raw materials and in the development of new constituents. The most important constituent observed was quartz. This mineral was noted in angular grains of variable size which showed practically no evidence of solution. The amount of quartz decreased from specimen 1 to specimen 4. Both the clay and the feldspar lost their original identity. The former melted to a low refracting glass, which increased in amount from specimen 1 to specimen 4. The clay dissociated almost entirely into silica and aluminum silicate. The silica dissolved in the feldspar glass but the aluminum silicate was apparently not soluble at this temperature. It was noted (1) mainly as amorphous sillimanite in minute rounded isotropic inclusions in the glassy groundmass and was distinguished from the groundmass by its index of refraction, which was greater than 1.60; (2) as a small quantity of true sillimanite occurring in extremely fine needle crystals about 0.01 mm in length. These were mainly apparently isotropic. Aggregates of these needles showing double refraction could be observed; the extinction was then noted parallel to the prism axis, the axis of elongation of the needles. The character of the principal zone was positive and the mean index of refraction was found to be about 1.64. The ratio of the amount of crystallized to amorphous sillimanite did not vary in specimens 1, 2, 3, and 4.

Specimens 5 to 10 (1310°).—These specimens resembled each other microscopically. The original quartz was noted unchanged and the angularity of the grains was proof that practically no solution had taken place. The amount of quartz decreased from specimen 5 to specimen 10. Both the feldspar and the clay lost their original identity. The feldspar melted to a low refracting glass which dissolved the silica, formed by the complete dissociation of the clay. The other dissociation product of the clay aluminum silicate, was observed both as amorphous sillimanite and as crystallized needles of sillimanite. As in specimens 1 to 4, the amount of the latter was much smaller than that of the former. Crystallites were very minute and often could be observed with only the highest magnifications.

Specimens 11 to 16 (1310°).—The data on the microscopical examination are very nearly the same for each specimen. The original feldspar melted entirely and the amount of feldspar glass increased from specimen 11 to specimen 16. The content of quartz decreased from specimen 11 to specimen 16, but the characters of the quartz grains were identical and the amount of solution in the feldspar glass was practically nil. The clay showed complete dissociation, with the formation of silica and amorphous and crystallized sillimanite. The silica dissolved completely in the glass. The sillimanite was noted mainly as amorphous sillimanite, with a very small amount of fine needle crystals, most of which were too minute to indicate birefringence.

Specimens 17 to 18 (1310°).—The microscopical examination of these specimens revealed a similarity to the previous specimens. The complete melting of the feldspar was noted, as well as the complete dissociation of the clay, with the formation of much amorphous sillimanite and a little crystallized sillimanite in very fine needles. As observed previously, the quartz showed practically no solution.

Specimens 1 to 4 (1400°).—These specimens (see Fig. 9) showed fundamental differences from those burned at 1320°. A considerable decrease was noted in the amount of free quartz, brought about by its solution in the glass. The solution was, however, by no means complete. The residual quartz grains were much rounded and etched. The solvent action proceeded more rapidly along the edges and along the fracture cracks of the quartz, resulting in rounded grains and in aggregates of rounded grains containing interstitial glass. The amount of residual quartz decreased from specimen 1 to specimen 4.

Another fundamental change noted was the great increase in number and to a lesser degree in size of the sillimanite needle crystallites, accompanied by a corresponding decrease in the amount of rounded inclusions. The tendency toward crystallization was noted by the attempts at elongation of some of the remaining amorphous sillimanite grains. These assumed a clublike form which could be observed only with higher magnification.

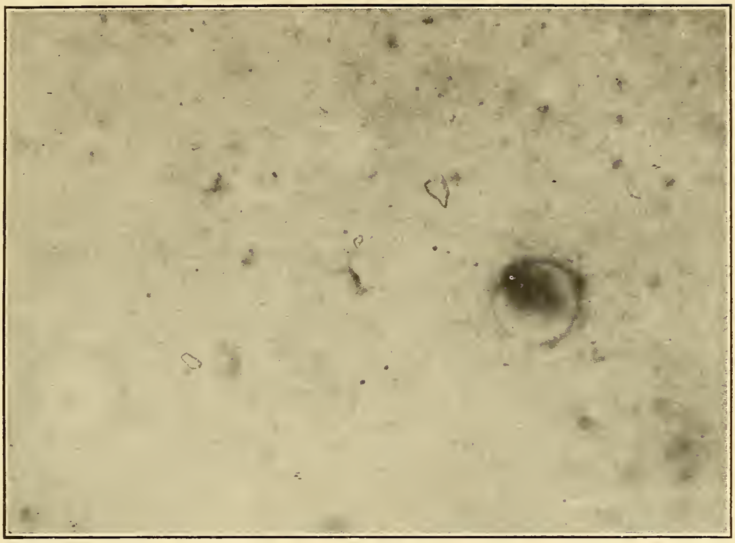

Fig. 6.—*Showing the body containing 55 per cent feldspar and 45 per cent quartz burned at 1460°. Note the last vestige of undissolved quartz grains. Magnification=300 diameters*

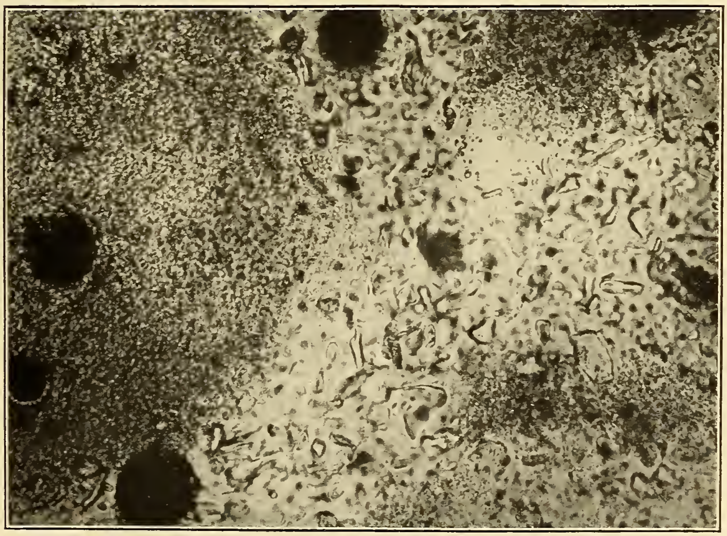

Fig. 7.—*Showing the body containing 90 per cent feldspar and 10 per cent kaolin burned at 1340°. Note the extremely fine-grained, intergrown, noncrystalline character of the amorphous sillimanite and the presence of undissolved quartz, which was originally introduced as an impurity in the feldspar and kaolin raw materials. Magnification=360 diameters*

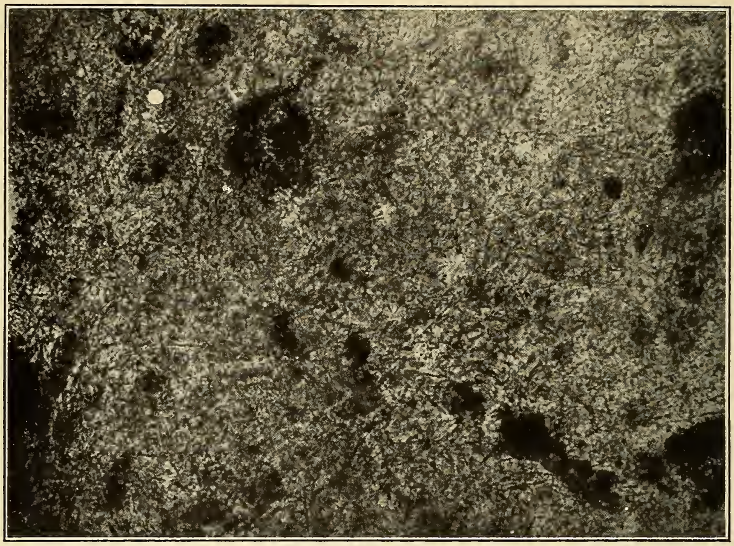

FIG. 8.—*Showing innumerable fine sillimanite needle crystallites developed by heating a body consisting of 50 per cent feldspar and 50 per cent kaolin to 1460°. Magnification=360 diameters*

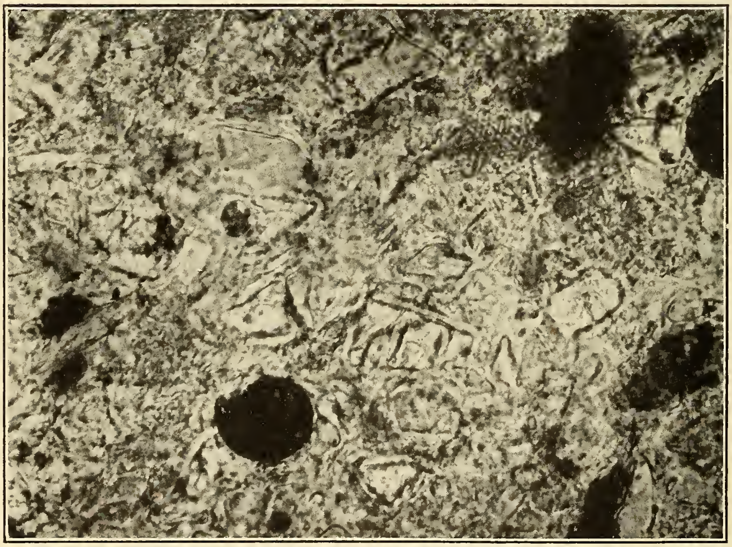

FIG. 9.—*Showing the body containing 35 per cent clay, 19 per cent feldspar, and 46 per cent quartz heated to 1400°. Note the presence of well-developed acicular sillimanite crystals, which in one instance exhibit typical lattice structure. Note also the considerable solution of the quartz. Magnification=500 diameters*

The amount of glass increased from specimen 1 to specimen 4. Moreover, owing to the increased solution of quartz, the amount of glass in each of the specimens was greater than the amount in the specimens burned at 1310°.

Specimens 5 to 10 (1400°).—The changes involved in raising the burning temperatures from 1310° to 1400° were identical with those observed in specimens 1–4. Quartz showed a considerable decrease in quantity, and the residual quartz grains bore evidence of solution, viz, rounding and etching of the grains. The amount of quartz decreased from specimen 5 to specimen 10.

Sillimanite needles were noted in much greater amount than the amorphous sillimanite. These were in most instances very minute, but occasionally individuals were noted 0.02 mm in length. They occurred mainly in irregular aggregates, but aggregates showing parallel grouping and the lattice structure described previously were also noted. The small crystallites were apparently isotropic while the larger ones sometimes showed the first order yellow interference color. Extinction parallel to the axis of elongation was noted and the principal zone was positive. Biaxial interference figures could occasionally be observed with a positive optical character, and the plane of the optic axis was parallel to the axis of elongation. Quantitative values for the indices of the α, β, and γ rays could not be obtained because the crystallites were much intergrown with glass and this could not be completely separated from them. The approximate mean index was found to be slightly above 1.64. These optical properties establish the compound definitely as sillimanite, $Al_2O_3.SiO_2$. The amount of glass increased from specimen 5 to specimen 10.

Specimens 11 to 16 (1400°).—The report of the microscopical examination of specimens 11 to 16 is similar to that of the preceding subseries. The considerable decrease in the amount of quartz with the corresponding increase in the quantity of glass was noted. The quartz grains were rounded and etched. They showed solution along the edges and along the fracture cracks.

Observations on the increase of the amount and to a lesser degree of the size of sillimanite needles were made. The development of sillimanite between 1300° and 1400° was similar to that observed with the previous specimens of series I. The incipient formation of sillimanite needles from amorphous sillimanite was also noted in the elongation of the rounded grains to form clublike grains and in the cementing or agglomeration of a number of these rounded inclusions to form a prismlike crystal.

Specimens 17 to 18 (1400°).—The observations on specimens 17 and 18 burned at 1400° are similar to those of the preceding specimens burned at this temperature. The amount of quartz noted was considerably less than that noted at 1300°, and the grains showed evidence of much solution. A corresponding increase in the amount of glass was also noted. The sillimanite needles, while greatly in excess of the extremely small amount of amorphous sillimanite, showed no better needle crystal development than in the previous specimens of series 1, where the quantity of original clay was smaller.

2. SECOND SERIES (LOW QUARTZ, HIGH FELDSPAR).—The specimens of this series were prepared and used by Bleininger and Kinnison in their study on the viscosity of porcelain bodies.[20] As with series 1, the data on the composition and burning will be presented but briefly here since they are given in fuller detail in the report of their investigation.

The compositions are indicated in Table 3 and Fig. 1. The figures in this table do not represent the true analysis of the burned specimens, but are only approximate, since they were calculated from the analyses of the same raw materials employed in series 1 and given in Table 1. From the data on composition it is evident that some of these specimens are identical with typical porcelain and floor tile bodies. The firing of all specimens with the exception of specimens 2, 4, and 5 was carried to 1275°, 1295°, 1315°, 1345°, and 1380°. The maximum temperature attained with specimens 2 and 5 was 1345°, and with specimen 4 was 1315°.

From a consideration of Table 3 it is seen that the series may be subdivided into four subseries in which the clay content is constant and the feldspar varies with the quartz. These are as follows: 35 per cent clay, 30 to 65 per cent feldspar, 35 to 0 per cent quartz; 40 per cent clay, 40 per cent feldspar, 20 per cent quartz; 45 per cent clay, 30 to 55 per cent feldspar, 25 to 0 per cent quartz; 50 per cent clay, 30 to 50 per cent feldspar, 20 to 0 per cent quartz.

Specimens 1 to 5.—Not all the specimens of this subseries can be compared with each other, since the maximum burning temperature was 1315° in the case of specimen 4, 1345° in the case of specimens 2 and 5, and 1380° in the case of specimens 1 and 3.

The microscopic examination of specimen 4 revealed the complete melting of the feldspar to an isotropic glass. The quartz bore evidence of only a slight solution as attested by the incipient rounding of the edges of especially the smaller grains. Extremely fine sillimanite needles were noted, as was also amorphous sillimanite. The needles were so minute as to be observed with only higher powers and only in a few instances could even the faintest interference colors be seen.

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[20] Trans. Am. Ceram. Soc., 17, pp. 130–136; 1915.

The complete melting of the feldspar and the solution of quite a little quartz was observed in specimens 2 and 5. Not all the quartz had disappeared even in specimen 5 where the quartz present occurred only as an impurity in the clay and in the feldspar, a very small amount being noted in more or less rounded grains. Sillimanite needles appeared to be more plentiful than in specimen 4 and slightly better developed, whereas amorphous sillimanite occurred in smaller amount.

Considerable solution of quartz was observed in specimens 1 (see Fig. 10) and 3, the latter containing an extremely small amount of undissolved quartz. No amorphous sillimanite was noted, since it was changed completely to the crystallized form. Although they appeared to be better developed than those of specimens 2, 4, and 5, the major portion of the needle crystals was still very minute. Optical properties when obtained agreed with those given for sillimanite.

Specimen 6.—The final burning of specimens 6 to 13 reached a maximum temperature of 1380°. Specimen 6 showed considerable solution of the quartz in the glass. There was no amorphous sillimanite noted, and the needle crystals were for the most part minute and irregularly intertwined.

Specimens 7 to 10.—Considerable solution of the quartz was also noted in the specimens of this subseries. Specimen 9 contained only a very small amount of residual quartz observed in rounded grains showing a large amount of solution. Specimen 10 contained only a trace of quartz. Sillimanite was noted in thin acicular crystallites, which occasionally showed parallel grouping and lattice structure, although they were mainly irregularly intergrown. The amount of glass increased from specimen 7 to specimen 10 with a corresponding decrease in the amount of quartz, while the amount and development of the sillimanite in the specimens showed no appreciable differences.

Specimens 11 to 13.—The conditions existing in this subseries were analogous to those in the previous subseries. Solution of the quartz took place to a considerable degree, and the residual quartz grains were very much etched and rounded. That complete solution did not take place was evidenced by a trace of quartz noted in specimen 13, where it occurred only as an impurity in the feldspar and the clay raw materials. (See Fig. 11.) Practically no amorphous sillimanite was noted. The sillimanite crystallites varied in size from minute needles showing apparent isotropy to some about 0.05 mm in length, in which first order interference colors were observed and which agreed with the mineral sillimanite in the determinable optical properties.

G. PORES, COMMUNICATING AND SEALED

In all the specimens examined in this investigation bubbles have been noted more or less regularly. No especially close observations have been made on these, since most of them were destroyed in the preparation of the specimens for examination, which was effected by tapping to a fine powder. In general our observations have been that a porous structure with communicating pores in greater amount than sealed pores is present in bodies burned at lower temperatures (for example, the temperature of burning of whiteware bodies). With increase in burning temperature the communicating pores decrease and the sealed pores increase; but with still further increase in burning temperature, for example, in hard-fired porcelain bodies, the sealed pores also decrease, although no body was examined in which they had totally disappeared.

H. RESULTS OBTAINED FROM THE STUDY OF LABORATORY-PREPARED BODIES

Kaolin suffers little optical change when heated up to 1200°. At this temperature the grains appear to be homogeneous and isotropic, with an index slightly higher than that given for the mineral kaolin. Above this temperature a slow incipient dissociation occurs up to about 1400°, when the material is entirely dissociated into what appears to be amorphous silica and amorphous sillimanite. When heated to 1450° the latter gives rise to characteristic needle crystals of sillimanite. When a flux—for example, feldspar—is present this dissociation proceeds at lower temperatures, and the silica loses its identity by solution in the feldspar melt. Thus, at 1340° kaolin is entirely dissociated with the formation of both amorphous and crystalline sillimanite, and with still higher temperatures the amorphous modification crystallizes entirely and the sillimanite crystals develop in size.

The investigation of the quartz-feldspar series shows that quartz is but slightly soluble in a feldspar melt at 1340°, but that with increase in temperature solution proceeds to a greater extent, and that at 1460° in melts which originally contained 50 per cent quartz there exists no more than a trace of undissolved quartz.

The study of the clay-quartz-feldspar series reveals a number of interesting facts. The feldspar is the first constituent to melt. It then acts as a flux-solvent in the solution of the other constituents. In both high quartz, low feldspar and low quartz, high feldspar bodies, burned at 1310° the original clay dissociates into both amorphous and crystalline sillimanite, the former greatly predominating. The sillimanite needles are so extremely small that they often appear isotropic with crossed nicols. Quartz is only slightly soluble at this temperature and the quartz grains show distinct angularity with little evidence of solution along the edges.

At higher temperatures (1380° to 1400°) the amorphous sillimanite disappears and gives rise to crystallized sillimanite. These crystals appear to grow somewhat in length and thickness, and parallel grouping and lattice structure are often noted. Quartz also dissolves to a considerable extent, and the residual grains of this constituent show much rounding of the corners and edges. In fact, the tendency is toward elliptical and spherical grains.

At this point we are led to a discussion of the question of the comparative solubility of kaolin and quartz in feldspar. Such a question is in the light of this investigation manifestly an indefinite one. What is meant by the solubility of kaolin? It has been definitely shown that kaolin dissociates into silica and aluminum silicate. It has been indicated also that the resultant silica is soluble in the feldspar glass, but that at the maximum temperatures attained in this investigation, 1460°, the aluminum silicate is comparatively little soluble. Therefore, to consider the solution of kaolin in feldspar at temperatures of porcelain burning is to consider an action which does not take place. However, if the criterion of the action of feldspar on kaolin is to be the solution in the feldspar melt of the silica resulting from the dissociation of the kaolin then such a comparison can be readily made. Unqualifiedly it is as follows: Kaolin is more soluble in feldspar than quartz under conditions of temperature and time analogous to those of porcelain practice.

I. THE TEMPERATURE OF BURNING, CONSTITUTION AND MICROSTRUCTURE SCALE

As stated previously, it was hoped that there was a fairly definite relationship between the burning temperatures of porcelain bodies and the physical and chemical changes taking place in the raw materials and noted in the microscopical examination of the finished product. That such is generally the case may be seen from the results of the study of the feldspar-quartz, feldspar-kaolin, and feldspar-quartz-clay series. Therefore, relying on such a relationship, the burning temperatures of commercial porcelain bodies were predicted from the microscopic examination. The actual burning temperatures were not known to the author, but Prof. A. V. Bleininger possessed the complete data, and a comparison of both showed that the predicted temperature of burning was remarkably close to the measured temperature. In fact an accuracy within 25° C was maintained in nearly all cases. The relation between constitution and burning temperature is given in Table 4.

J. COMMERCIAL BODIES

This series embraces bodies ranging from a white-ware body to a high-fired hard porcelain body. The technical practices of many countries are represented in order to determine the essential differences in constitution and microstructure effected in bodies of the same commercial class by dissimilar conditions of burning. The practices of the following countries are represented: United States, England, Germany, France, Austria, Denmark, and Japan.

1. *White-ware, Ohio.*—The following constituents were noted: Feldspar glass, dehydrated clay, and quartz. The feldspar appeared to have entirely melted to a glass. The dehydrated clay was noted as amorphous grains which showed practically no evidence of dissociation into lower refracting silica and higher refracting amorphous sillimanite. The quartz grains were noted in considerable amount. They varied in size from almost submicroscopic grains to grains measuring 0.5 mm across, and showed absolutely no evidence of solution in the feldspar glass. The melting of the feldspar and the absence of dissociation of the clay were evidence of the fact that the burning temperature of this body was not over 1200°.

2. *White-ware Body (Unknown Brand).*—The microscopical examination revealed the following facts: The feldspar had entirely melted to a glass acting as a cement for the other constituents.

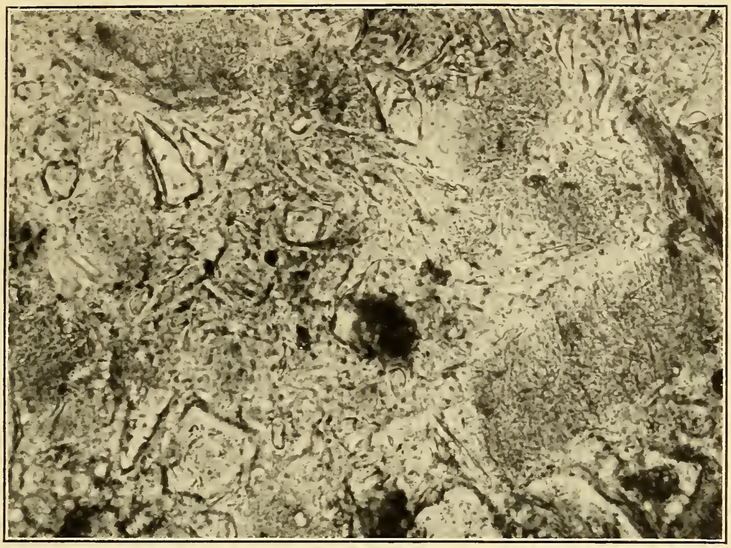

FIG. 10.—*Showing the body with a composition of 35 per cent clay, 30 per cent feldspar, and 35 per cent quartz burned at 1380°. Note the development of crystallized sillimanite and the evidence of considerable quartz solution. Magnification=380 diameters*

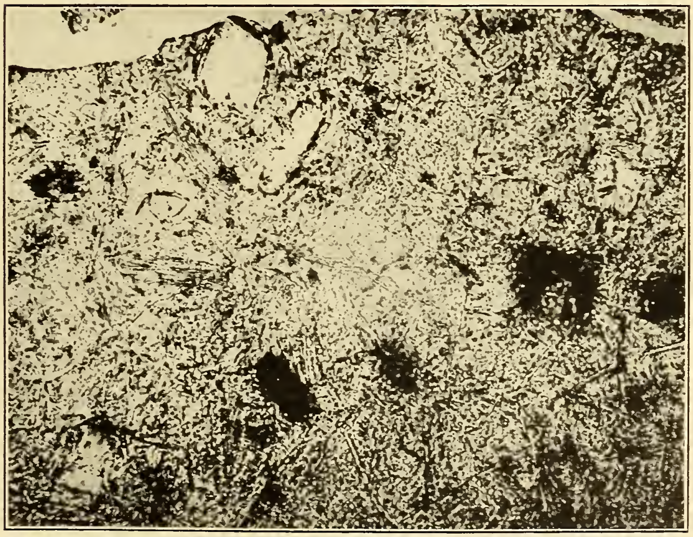

FIG. 11.—*Showing the body composed of 50 per cent feldspar and 50 per cent clay. Note the development of sillimanite needles and the presence of an extremely small amount of residual quartz in mainly elliptical grains. Magnification=300 diameters*

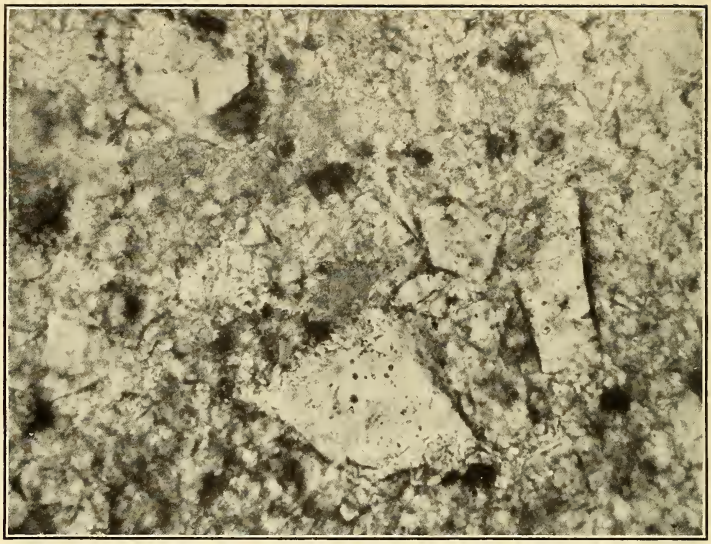

Fig. 12.—*Showing a specimen of vitrified tableware manufactured in New York. Note the absence of sillimanite needle development and the presence in the groundmass of cloudy material whose structure can not be resolved in a thin section but which is due to the presence of minute amorphous sillimanite grains. Note also the large quartz grains showing absolutely no solution. Magnification=300 diameters*

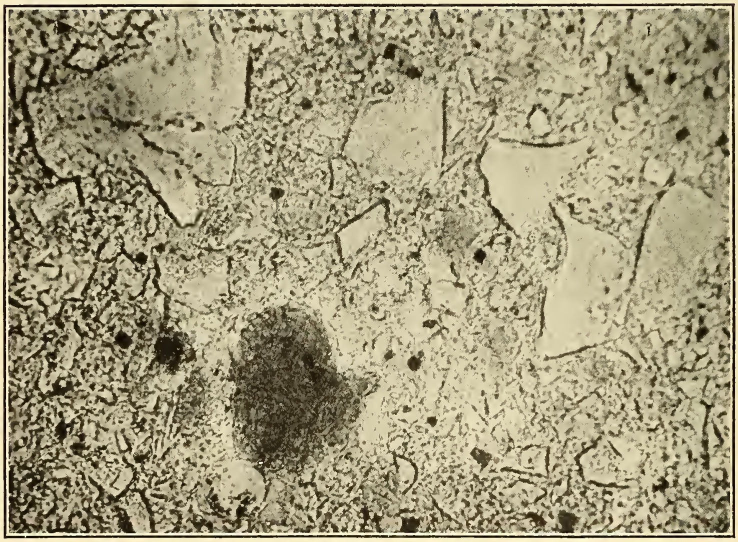

Fig. 13.—*Showing a vitrified tableware manufactured in Pennsylvania. Note the sharp angled undissolved quartz grains and an aggregate of very minute sillimanite needles showing lattice structure. Magnification=380 diameters*

Nearly all the dehydrated clay was unchanged. That an extremely small part did dissociate was evidenced by the presence of minute rounded amorphous sillimanite grains of higher index than the other constituents occurring as inclusions in the dehydrated clay grains and in the glass. Quartz was present in considerable quantities, but the grains showed no evidence of solution. The melting of the feldspar and slight dissociation of the dehydrated clay material indicated a burning temperature of 1200° to 1225°.

3. White-ware, J. & G. Meakin; Hanley, England.—The feldspar melted to a glass acting as a bond for the other constituents. The observations on the clay were very unsatisfactory. There was considerable undissociated dehydrated clay present, but some of it appeared cloudy and brownish in color. The microscope did not resolve anything further of the structure of these brownish grains; so this condition is probably due to the presence of amorphous sillimanite grains, which are just submicroscopic in size. The quartz, while not so plentiful as noted in the two American white ware bodies, was found in sharp cornered grains giving no evidences of solution. The indications were of a burning temperature between 1200° and 1225°.

4. Vitrified Tableware, West Virginia.—A considerable dissociation of the dehydrated clay was noted, with the formation of minute rounded isotropic grains of amorphous sillimanite and a trace of extremely fine needles of sillimanite. The silica resulting from the dissociation lost its identity in the feldspar glass. Quartz was present in a considerable quantity and showed absolutely no evidences of solution. The partial dissociation of the clay indicated a temperature of burning of about 1250°.

5. Vitrified Tableware, New York.—The examination of this specimen showed that the feldspar had melted completely. The dehydrated clay had dissociated to a considerable extent to amorphous sillimanite mainly, with only a trace of minute sillimanite needles. A large quantity of quartz was noted, and the quartz grains bore no evidence of solution. (See Fig. 12.) The constitution of this specimen indicated a burning temperature of about 1250°.

6. Sanitary Body, New Jersey.—The microscopical evidence in this body was analogous to that of the two preceding specimens. The feldspar had melted completely to a low-refracting glass. The quartz grains showed no apparent solution. The dehydrated clay showed considerable dissociation into amorphous sillimanite and an extremely small amount of fine sillimanite needles, all of which indicated a burning temperature of about 1250°.

7. *Vitrified Tableware, Pennsylvania.*—The constitution of this body was identical with that of the previous vitrified bodies burned according to American practice. (See Fig. 13.) The dehydrated clay had dissociated quite considerably to the minute intergrown isotropic material called amorphous sillimanite and a small amount of fine sillimanite needles which were not sufficiently developed to exhibit interference colors. The quartz grains showed no evidence of solution and the largest one observed measured 0.14 mm. in length. The burning temperature may be estimated as being about 1250°.

8. *Japanese Porcelain, Nippon (A).*—The translucency of this specimen was greater than that of the American bodies. In fact it compared favorably with the high-fired ware described later. The microscopic observations revealed the fact that its translucency was due to a comparatively high content of feldspar and low content of clay and did not result from hard burning. The clay showed considerable dissociation but the amount of crystallized sillimanite present was hardly more than a trace. Moreover, notwithstanding the amount of flux, the grains of quartz bore no evidence of solution (see Fig. 14), and the largest one observed measured 0.18 mm. It is evident from the above data that the burning temperature of this body was not over 1250°.

9. *Electrical Porcelain, Pennsylvania.*—The important feature of this specimen (see Fig. 15) was the almost complete dissociation of the dehydrated clay with the formation of considerable amorphous sillimanite and a much less amount of minute sillimanite crystallites. There was only a very small quantity of undissociated dehydrated clay present. The quartz grains showed only a trace of solution, if any at all, and were sharp cornered in nearly every instance. The feldspar had melted entirely to a glass. The almost complete dissociation of the dehydrated clay, the great preponderance of the minute rounded amorphous sillimanite grains over the sillimanite needle crystallites and the absence of any decided solution of quartz indicated a burning temperature of about 1250° to 1275°.

10. *Electrical Porcelain, New York.*—The constitution and the microstructure of this body was identical with that of the body previously described. The important features were the almost complete dissociation of the dehydrated clay material, with the

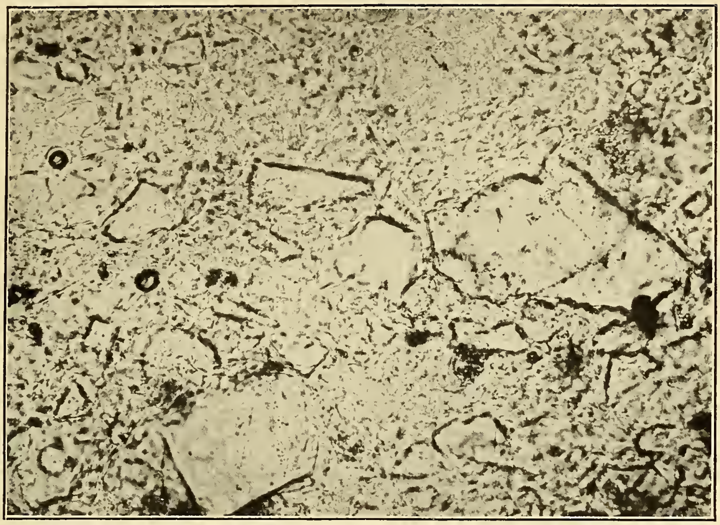

FIG. 14.—*Showing a Japanese porcelain. Although this ware was very translucent, the evidence of low burning is very evident. The quartz grains are angular and only a trace of minute sillimanite needles is noted. Magnification=380 diameters*

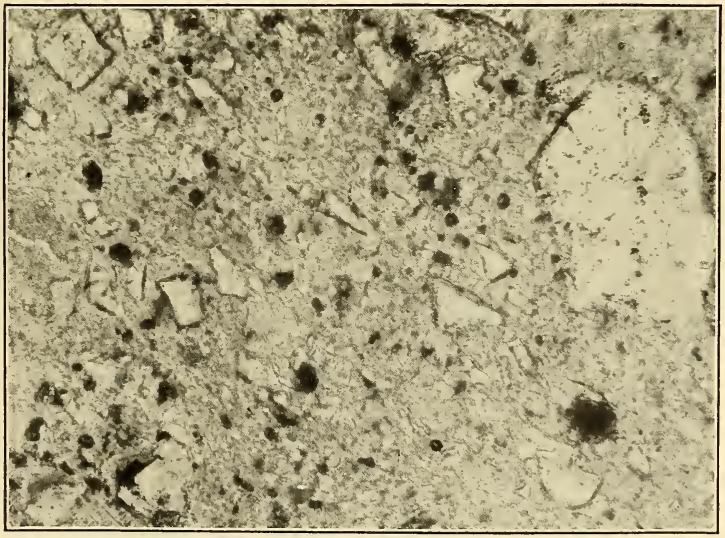

FIG. 15.—*Showing an electrical porcelain body manufactured in Pennsylvania. Note the variation in size of the quartz grains and the absence of any evidence of quartz solution. No crystalline sillimanite can be definitely seen in the photograph, but the cloudiness in the groundmass, due to amorphous sillimanite, may be readily recognized. Magnification=300 diameters*

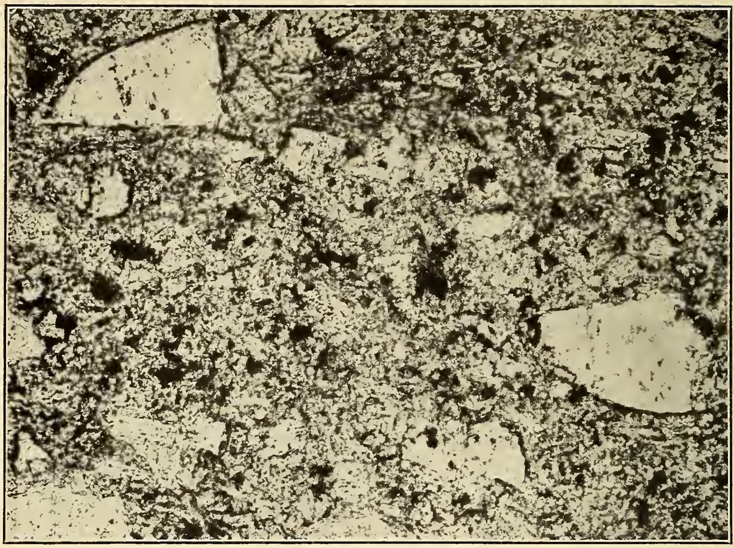

Fig. 16.—*Showing an electrical porcelain body manufactured in New York. Note the sharp-cornered irregular quartz grains and the presence of a trace of sillimanite needles which may be observed at the lower left corner of the photomicrograph. Magnification=180 diameters*

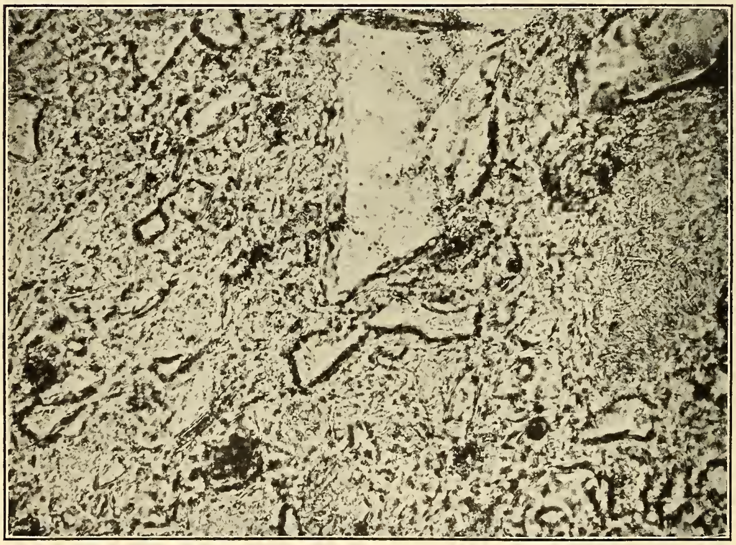

Fig. 17.—*Showing a Japanese porcelain. Note the sillimanite development which is better than in Fig. 14, and the complete absence of quartz solution. Magnification=380 diameters*

resultant formation of only an extremely small amount of crystallized sillimanite in minute needles. The quartz grains bore no evidence of solution. (See Fig. 16.) The burning temperature as indicated by the microstructure, was probably 1250° to 1275°.

11. Spark-Plug Body.—The following observations were made on this body. A low refracting glass resulting from the melting of the feldspar was observed. The dissociation of the dehydrated clay had proceeded to a great extent with the formation of amorphous sillimanite and sillimanite needle crystallites, of which the former greatly predominated. Quartz was present in considerable amount and appeared to have undergone no solution in the larger grains and a doubtful trace of solution in the smaller ones. The microscopical evidence here was identical with that of the previous specimens, and the burning temperature appeared, therefore, to be about 1275°.

12. Japanese Porcelain, Nippon (B).—This specimen appeared to be higher fired than the Japanese specimen (A) previously examined. The dehydrated clay was greatly dissociated and the amount of crystallized sillimanite, while still fairly small, was nevertheless greater than in the specimen referred to above. (See Fig. 17.) The largest quartz grain observed had a length of 0.19 mm, and with the possible exception of a trace in the smallest grains, the quartz present showed no evidence of solution. The above facts warrant an estimation of about 1300° as the burning temperature.

13. Bavarian Porcelain, Hübschenreythe.—At best but a slight solution of quartz in the feldspar glass was noted in this specimen. The grains possessed sharp edges, and evidences of slight solution were not general, being noted mainly in the smaller quartz grains. While there was little if any undissociated dehydrated clay present, the main dissociation product was amorphous sillimanite in minute rounded grains. A small amount of crystallized sillimanite was also present. The almost complete dissociation of the dehydrated clay, together with the preponderance of amorphous over crystallized sillimanite, pointed to a burning temperatnre of about 1300°.

14. Austrian Porcelain, Massburg.—The constitution and microstructure of this specimen were found to be identical with that of the Hübschenreythe body and will not be discussed further.

15. Silesian Porcelain.—The observations on this specimen were practically identical with those made on the Massburg and Hübschenreythe specimens. Very little crystallized sillimanite was observed, although the clay showed great dissociation. The evident finer grinding of the quartz raw material was of interest, the largest grain observed measuring 0.1 mm in length. The grains, as a rule, were sharp cornered, thin, and sliver-like in appearance. The smaller quartz grains showed but a trace of solution, while the larger ones were entirely undissolved. This specimen appeared to have been burned at a temperature not over 1300°.

16. Austrian Porcelain, Elsa.—The examination of this specimen revealed the complete dissociation of the dehydrated clay material and the resultant formation of both amorphous and crystalline sillimanite, the former occurring in larger amounts. A large quantity of quartz was present, and very slight evidence of solution was observed. The above data indicated a burning temperature of about 1300° to 1325°.

17. Chemical Porcelain, Bureau of Standards Body No. 10.—Complete dissociation of the dehydrated clay was observed in this specimen. The resultant sillimanite occurred in both the crystalline and the amorphous form, with the former as plentiful as the latter. The acicular crystallites of sillimanite were minute, extremely intergrown, and in nearly all cases they were apparently isotropic. The quartz grains gave evidence of a small amount of solution in the feldspar glass. That a greater degree of solubility was attained here than in the specimens burned at 1300° to 1325° was shown by a more universal etching and a more pronounced rounding of the quartz grains. When this examination was made the author was unaware of the burning temperature of the body, but from the above data he estimated the burning temperature to have been 1325° to 1350°. Subsequently he was informed by G. H. Brown, of this Bureau, who prepared and burned the body, that the temperature of burning was 1350°.

18. *Royal Meissen Porcelain; Onion Pattern.*—The microscopical examination of this body (see Fig. 18) revealed a microstructure which was practically identical with that of the previous body. The dissociation of the clay had taken place with the formation of very minute needles of sillimanite and rounded, intergrown, minute grains of amorphous sillimanite. The quartz content was fairly low, but the appearance of the individual quartz grains indicated a small but appreciable solution. The burning temperature seemed to be close to that of the chemical porcelain body No. 10, about 1325° to 1350°.

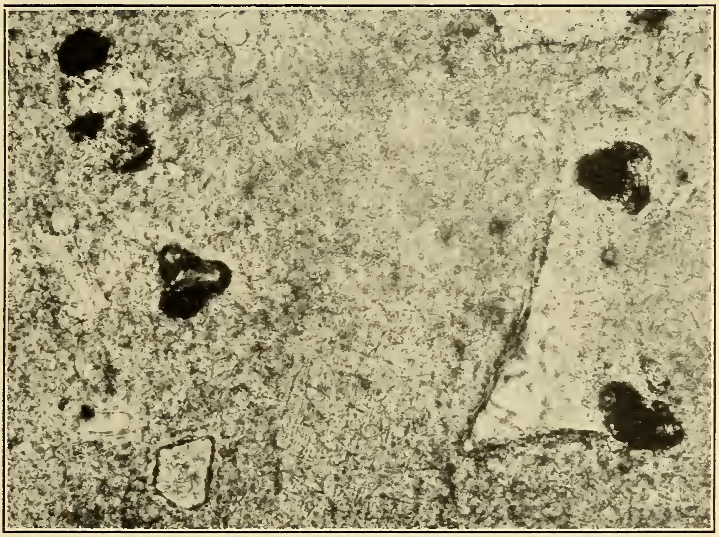

FIG. 18.—*Showing Royal Meissen porcelain; onion pattern. Note the presence of both amorphous and crystallized sillimanite. Only the smaller quartz grains show evidence of solution as manifested by the rounding of the grains, while the larger ones still retain their sharp corners. Magnification=300 diameters*

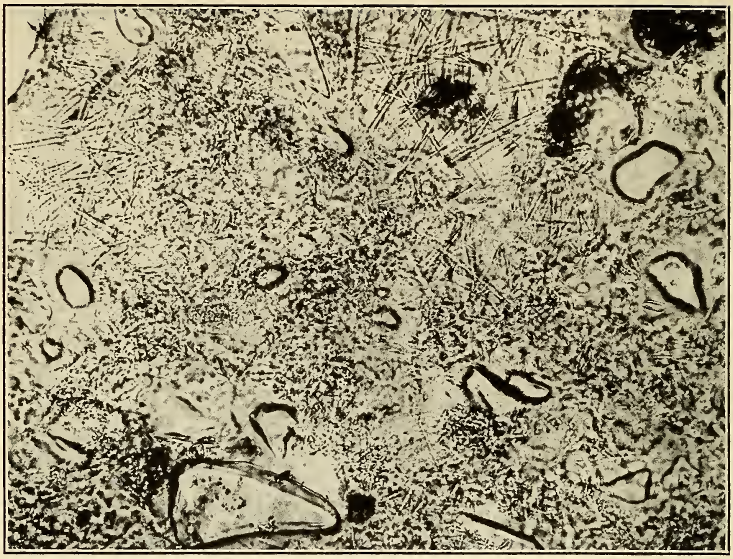

Fig. 19

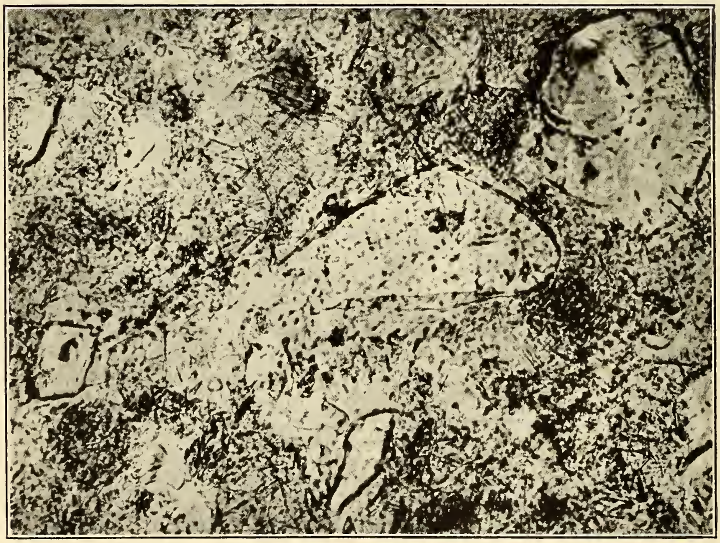

Fig. 20

Figs. 19 and 20.—*Showing a Japanese porcelain. Note the evidences of a higher burning than in the two Japanese porcelains previously described and photographed in Figs. 14 and 16. Sillimanite needles are extremely well developed and the quartz grains, both large and small, show the evidences of solution. Magnification=380 diameters*

19. *Japanese Porcelain, Nippon (C).*—This specimen seemed to be the highest fired of the three Japanese bodies examined. Complete dissociation of the clay was observed with the resulting formation of crystallized and amorphous sillimanite, the former being in excess of the latter. The sillimanite needles were larger and better developed than any observed in the previous specimens. The conditions were favorable to their growth since the original kaolin content appeared to have been comparatively low, and the reverse apparently was the case with the feldspar. The quartz grains showed unmistakable signs of solution. The larger grains possessed at least round corners and a tendency toward rounded edges, whereas the smaller ones were elliptical and spherical shaped, denoting considerable solution. (See Figs. 19 and 20.) The largest quartz grain observed measured 0.12 mm in length. The amount of crystallized sillimanite and the amount of quartz solution indicated a burning temperature of about 1350°.

20. *Limoges Porcelain, L. Bernardaud & Co.*—The clay of this specimen showed complete dissociation. The products of dissociation were mainly fine sillimanite needles and a comparatively small amount of minute intergrown amorphous sillimanite. The quartz gave evidence of a greater solution than in the previous specimen (see Fig. 21), the larger grains appearing more rounded. The largest grain of this mineral measured 0.12 mm in length. From the progress of the solution of quartz and the formation of crystallized sillimanite a burning temperature of 1375° was estimated.

21. *Limoges Porcelain, Ahrenfeldt.*—As in the case of the preceding specimen, the dehydrated clay had completely dissociated, and the dissociation had resulted for the most part in the formation of fine sillimanite needles and only a small amount of amorphous sillimanite. The quartz appeared to have undergone quite considerable solution in the glass, the etching and rounding of the grains being as pronounced as in the previous specimen. The evidence pointed to a burning temperature of about 1375°.

22. *Limoges Porcelain, Theodore Haviland.*—The dehydrated clay in this specimen had not only dissociated, but the amorphous sillimanite resulting from the dissociation had nearly all crystallized into needle crystals of sillimanite. These varied in size, being more generally very small. Occasionally, however, they possessed a length of 0.1 mm, and when of this size they exhibited anisotropy, parallel extinction, a positive principal zone, and

biaxial positive interference figures; all of which are observed on sillimanite. The needles occurred more often in irregular aggregates, but at times parallel grouping and the lattice structure previously described were observed. Quartz occurred in comparatively small amounts as rounded, sometimes almost spherical, grains. Aggregates of rounded grains were noted which were originally a single grain, but solution had taken place along fracture cracks and had disintegrated the large grains into smaller ones. That a considerable solution of quartz in the feldspar glass occurred is very evident. The crystalline sillimanite development and the solution of the quartz indicated a burning temperature of about 1375° to 1400°.

23. *Limoges Porcelain, Haviland, Ransom Plain Pattern.*—This specimen (see Fig. 22) showed an interesting constitution and microstructure typical of high feldspar, hard fired porcelains. The constituents in order of importance were glass, sillimanite crystallites and quartz. The sillimanite occurred in acicular crystallites. Parallel grouping and lattice structure were sometimes observed, although most of the crystallite aggregates possessed no regular orientation. Some of the needles were developed sufficiently so that first order yellow interference colors were observed with crossed nicols. The remaining optical properties agreed with those given for sillimanite. There were comparatively few minute rounded isotropic grains of amorphous sillimanite noted. The amount of undissolved quartz was not large, and the rounded to spherical appearance of the grains indicated the great progress which solution in the feldspar glass had made. The better development of sillimanite and evidence of greater solution of the quartz than in the Ahrenfeldt and Theodore Haviland bodies were taken to indicate a slightly greater burning temperature, probably about 1400°.

24. *Royal Berlin Chemical Porcelain.*—The microscopical examination of this body (see Fig. 23) as well as the succeeding chemical porcelain bodies revealed even a higher burning temperature than that of the Limoges practice. The most important constituent observed was the glass resulting from the melting of the feldspar and the subsequent solution in the melt of silica resulting from the dissociated clay, and of quartz. The sillimanite crystallites were much intergrown, and varied in size from almost submicroscopic needles to some which measured 0.1 mm or more. The residual quartz grains were present in very small amounts, and their elliptical to spherical outlines bore witness to the great amount of solution they had undergone.

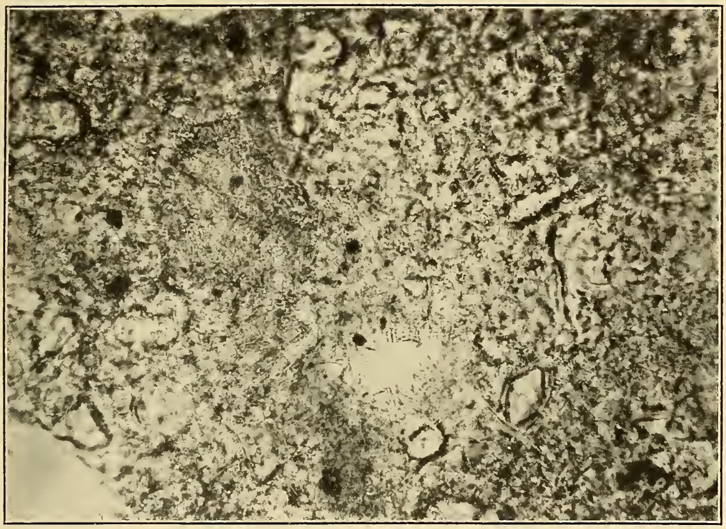

Fig. 21.—*Showing Bernardaud, Limoges, porcelain. Note the sillimanite needles and the rounded quartz grains. Magnification=380 diameters*

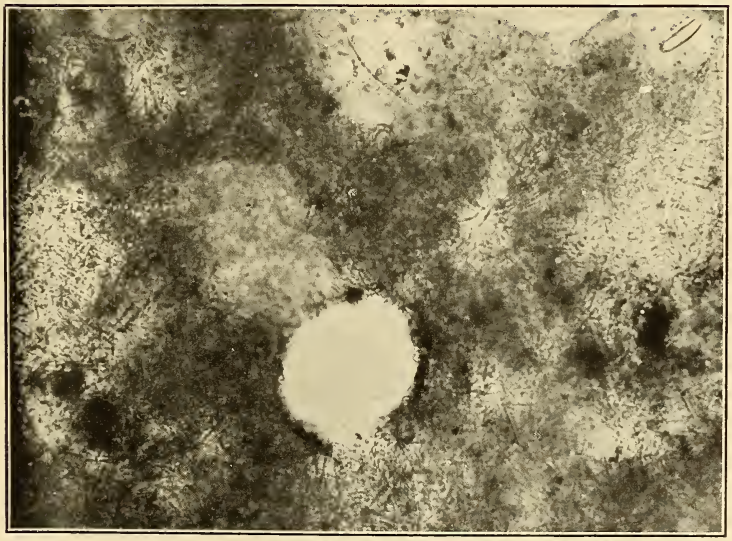

Fig. 22.—*Showing Haviland, Limoges, porcelain. Note the sillimanite development and the elliptically shaped quartz grains. Magnification=440 diameters*

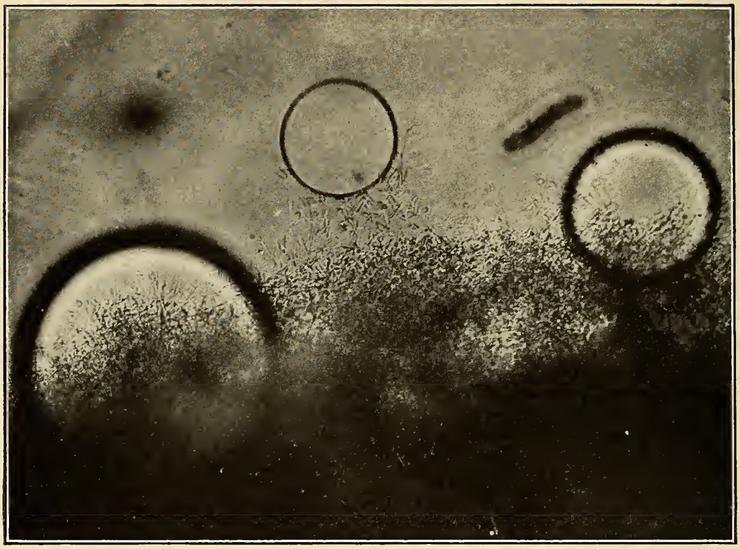

Fig. 23.—*Showing a fracture piece of Royal Berlin chemical porcelain consisting of both body and glaze, and demonstrating the reaction between them, occurring during the glost burn. Note the spherical blebs and the sillimanite needles extending from the body into the glaze. Because of the thickness of the fracture piece, the body appears opaque. Magnification=300 diameters*

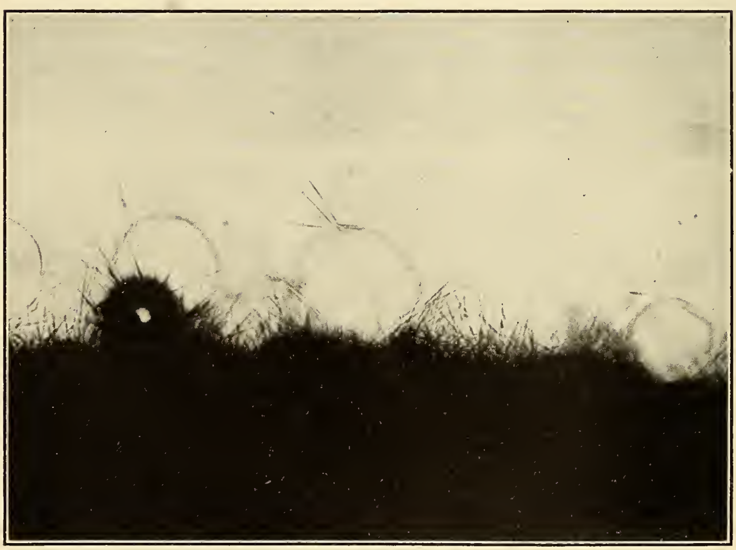

Fig. 24.—*Showing a fracture piece of Thuringian chemical porcelain consisting of both body and glaze. Note the similarity to Fig. 23 except that the sillimanite crystals are larger. Magnification=190 diameters*

The increase in the solution of quartz over that in the Limoges bodies pointed to a probable burning temperature of 1400° to 1425°.

25. *Thuringian Chemical Porcelain.*—This body resembles the Royal Berlin body in constitution and microstructure. (See Fig. 24.) The constituents in order of importance were, glass, sillimanite crystallites, and undissolved quartz. The crystals of sillimanite ranged in size from extremely minute needles to those upwards of 0.1 mm in length, and the optical properties of the largest needles, which showed unmistakable anisotropy, agreed with those given for sillimanite. Only a small amount of quartz was present, and the grains bore evidence of great solution. The similarity between the observations here and those of the previous specimen indicated a burning temperature of 1400° to 1425°.

26. *Royal Meissen Chemical Porcelain.*—This body resembles both the Thuringian and Royal Berlin bodies. (See Figs. 25, 26, and 27.) The sillimanite crystallites attained a maximum length of 0.23 mm and often exhibited parallel grouping and lattice structure. As may be expected, the quartz grains bore evidence of much solution. Often the residual quartz grains were surrounded by a zone of glass free from sillimanite crystallites; but almost as often these two constituents were intimately associated with each other. This observation was made not only with the Meissen body but with all the hard fired porcelains examined in which the quartz showed considerable solution. The above observations indicated a burning temperature of 1400° to 1425°.

27. *Chemical Porcelain; Bureau of Standards' Body No. 14.*—The constituents of this body were a low refracting glass, sillimanite crystallites and residual quartz grains. The needles of sillimanite were very plentiful and for the most part very minute and intergrown. The amount of unchanged quartz was small (not over 5 per cent). The burning temperature was estimated from the constitution as being very close to that of the last three chemical porcelains examined, viz, 1400° to 1425°. The actual burning temperature was 1425°. Of interest in showing the great solution of the quartz at this temperature is the composition of the porcelain clay 55 per cent, feldspar 20 per cent, and quartz 25 per cent.

28. *Royal Copenhagen Tableware.*—The microscopical examination of this body gave evidence of its being very hard fired. A large amount of extremely minute sillimanite crystals, formed as a result of the dissociation of the clay was noted. These were with

few exceptions so thoroughly intergrown that the structure could be resolved at all only with a high magnification (900 diameters or more). A small amount of residual quartz was noted, the grains varying in size from 0.18 mm to considerably less than 0.01 mm. The rounding of even the largest quartz grains was conclusive evidence of its great solution. (See Fig. 28.) From the microscopical study of this body it appears to have been characterized by a high kaolin and quartz content and a lower feldspar content. Its burning temperature appears to have been above 1425°.

29. *Royal Copenhagen Chemical Porcelain.*—This body greatly resembled the Copenhagen tableware body. The presence of glass and sillimanite was noted. The amount of sillimanite appeared to be greater than was observed in the other chemical porcelains. The crystal development, however, was not particularly remarkable. In fact, almost all the sillimanite needles were very minute and exceedingly intergrown. The criterion for the burning temperature was the almost complete absence of quartz. The few quartz grains which were observed were for the most part so minute as to appear isotropic with crossed nicols, and could be recognized only by the indices of refraction. There were some quartz grains present, however, which were unmistakably uniaxial and positive, but these also were much rounded and etched by solution. The evidence indicated a burning temperature higher than 1425°.

30. *English Bone China.*—This body does not fall in the category of the porcelain bodies examined in this investigation. According to B. Moore [21] a normal bone china body consists of: Bone ash, 44 per cent; cornwall stone, 30 per cent; and china clay, 26 per cent. Quartz and feldspar may be substituted for Cornwall stone. Mellor [22] from a microscopical study, states that "a correctly fired bone china body is almost a vitreous homogenous mass," and that in "easy" fired bone china, "a few fragments with blurred edges, possibly undissolved fragments of bone ash, china clay or silica, remain."

The bone china specimen examined in this investigation consisted almost entirely of isotropic material. This isotropic material was, however, not homogeneous, but consisted of two substances, both of which were extremely fine grained and intimately intergrown. One possessed a refractive index equal approxi-

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[21] Transactions Eng. Ceramic Society, 5, p. 37.

[22] Clay and Pottery Industries, 1, p. 24.

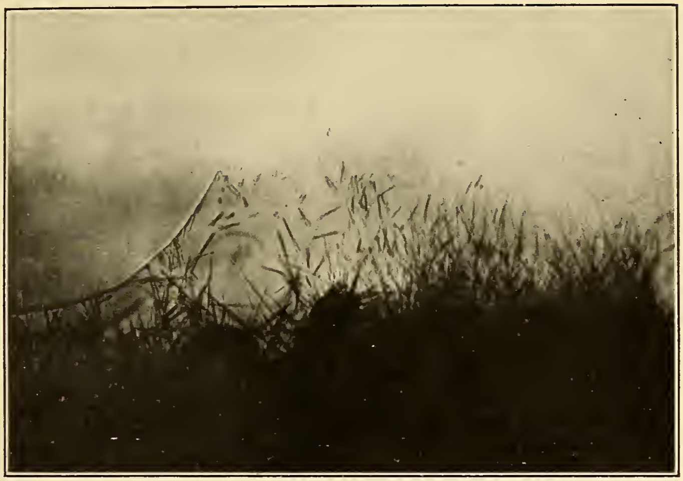

FIG. 25.—*Showing a fracture fragment of Royal Meissen chemical porcelain. Note the similarity to Fig. 24. Magnification=300 diameters*

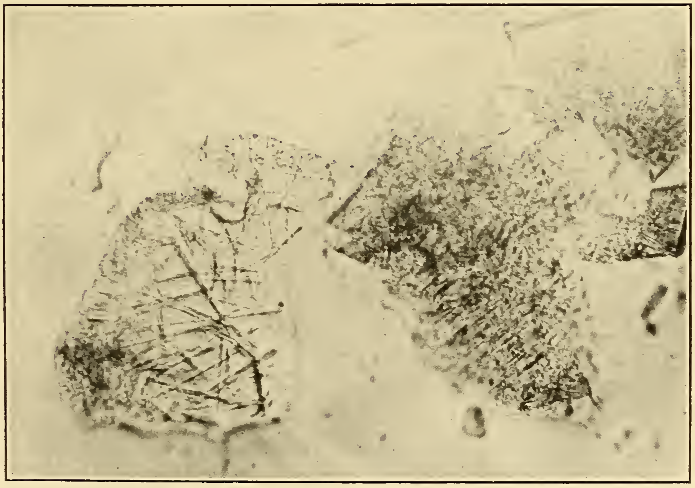

FIG. 26.—*Showing fracture fragments of a Royal Meissen chemical porcelain body magnified greater than that of Fig. 25. Note the excellent sillimanite development. Magnification=600 diameters*

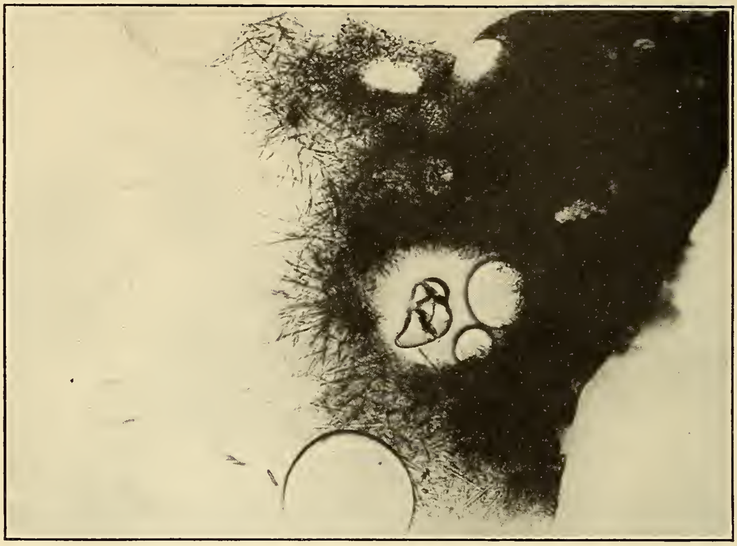

FIG. 27.—*Showing a fracture piece of Royal Meissen chemical porcelain consisting of body and glaze. This photograph is very interesting in that it shows not only the sillimanite needle development and blebs between the body and glaze, but also a grain of quartz exhibiting typical evidence of solution around the edges and along fracture cracks. Magnification=190 diameters*

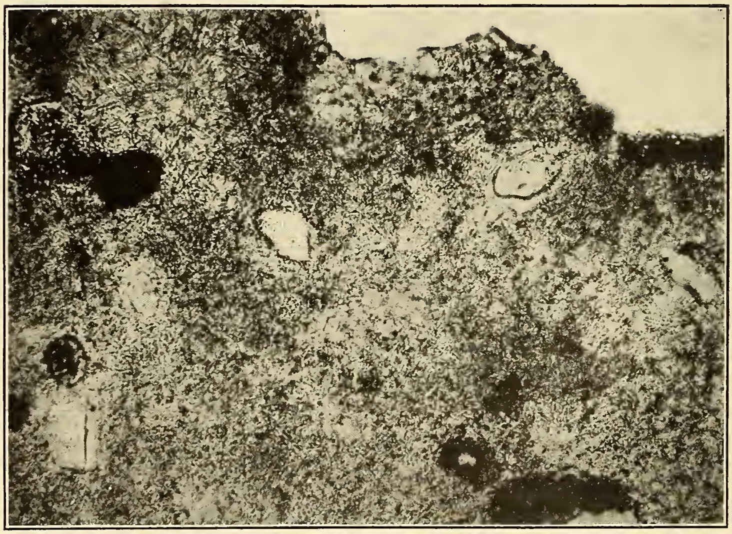

FIG. 28.—*Showing Royal Copenhagen tableware. Note the remnants of quartz showing great solution and the sillimanite needle development which is most often obscured by intergrowth but appears verv distinct in one portion of the field. Magnification=380 diameters*

mately to 1.53, and the other an index equal approximately to 1.61. The lower refracting material resembled the glass noted in ordinary vitrified feldspar-clay-quartz bodies, although its comparatively high refractive index suggests that possibly the phosphate glass and the feldspar glass are mutually soluble. The higher refracting material occurred in irregular to rounded minute grains resembling that product noted previously and called amorphous sillimanite. In addition, a small amount of quartz was observed in grains which were fairly angular. (See Figs. 29 and 30.) These grains were noted up to 0.12 mm in length.

K. THE RELATION OF MICROSTRUCTURE AND CONSTITUTION TO TIME OF BURNING

From the data obtained by the investigation of bodies prepared in this laboratory and of commercial bodies, it has been noted that there are marked differences in microstructure and constitution depending upon differences in burning temperature. The question now arises whether there are not great differences in constitution entailed in the ordinary differences in time of burning, since this factor may vary in the practices of individual concerns? Undoubtedly there are some differences, but these are relatively small when compared with changes involved with the variation of the burning temperature. For instance, the Bureau of Standards chemical porcelain body No. 14 was burned at 1425° and the Royal Berlin chemical pocelain was burned at cones 15 to 16, about the same temperature. The data on the microstructure and constitution of these two bodies are practically identical, notwithstanding the fact that the burning of our body lasted about 24 hours from beginning to completion, the kiln being kept for 3 hours at the maximum temperature, whereas in European practice the time of maintaining the highest temperature range may be as long as 12 hours.

Another comparison may be made between chemical porcelain body No. 14 and the specimens of the feldspar-quartz-clay series I, which had received 10 successive burnings from 1065° to 1400°. The constitution of the latter bodies, notwithstanding their excessive burning, indicated a slightly lower burning temperature than the former. The quartz, for instance, did not show quite the effect of solution in the feldspar glass in any of the specimens of series I as in body No. 14. This fact is indeed fortunate from the viewpoint of predicting the burning temperature from the microscopical examination of the burned product. If there were great differences in constitution caused by small differences in duration of burning, a low temperature body burned for a longer period would resemble a high temperature body burned for a shorter period. Fortunately this is not the case.

L. THE ABSENCE OF CRISTOBALITE AND TRIDYMITE FROM HARD PORCELAIN BODIES

As has been mentioned previously, quartz inverts to tridymite at 875° and to cristobalite at 1475° in the presence of sodium tungstate as a flux. Furthermore, we [23] have observed, in the burning of silica brick, the change of quartz direct to cristobalite at higher temperatures in the presence of only a slight amount of flux. Recently we have also noted the change of cristobalite to tridymite when the silica brick have been subjected many times to high temperatures under 1475°. Why, then, should we not observe these modifications instead of the residual quartz grains? The determination of cristobalite and tridymite in a porcelain is a matter of difficulty, since these two compounds have such a low double refraction as to appear isotropic, or nearly so, in small grains, and furthermore, the glass noted in porcelain varies in index, depending upon its composition, although its index is always in the vicinity of the indices of these two compounds. A thorough and painstaking search has thus far revealed no definite appearance of cristobalite and tridymite, while the presence of residual quartz has been demonstrated in all cases. It is probable, therefore, that solution of the quartz in the glassy constituent takes place more rapidly than its inversion to cristobalite and to tridymite. Otherwise we ought to find unmistakable evidence of the presence of these compounds.

IV. SUMMARY AND CONCLUSION

The investigation consisted in the microscopic petrographic examination of kaolin, feldspar-quartz, feldspar-kaolin, and feldspar-quartz-clay bodies burned at various known temperatures. Furthermore, commercial bodies of various grades ranging from white ware to hard fired porcelain were investigated. The end in view was to obtain data as to the constitution and microstructure of porcelains and the changes in these involved by burning at various temperatures. Subsequently it was found possible to

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[23] Met. Chem. Eng., **13**, pp. 861–866; 1915.

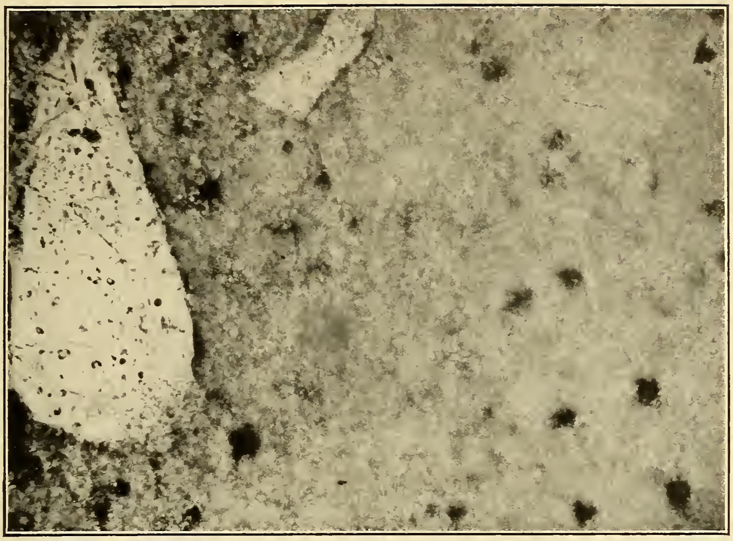

Fig. 29.—*Showing English bone china. Note the undissolved quartz grains and the heterogeneous character of the groundmass. Magnification=380 diameters*

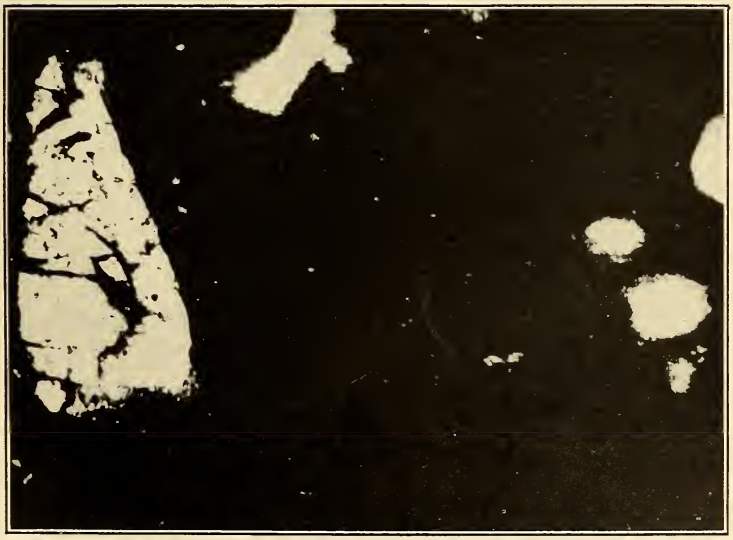

Fig. 30.—*Showing the same field as that of Figure 29 taken in plane polarized light with crossed nicols. This photograph serves to contrast the birefringent quartz with the isotropic groundmass. Magnification=380 diameters*

correlate to a certain degree the constitution and microstructure with the burning temperature of bodies whose composition lay within the limits of white ware and hard fired porcelains.

This investigation leads to the following conclusions: Kaolin appears homogeneous microscopically when heated up to 1200°. At about this temperature a trace of dissociation occurs. As the temperature is raised above 1200° the dissociation increases very slowly at first, then at an increasing rate, until at 1400° it seems to be complete. The products of dissociation are silica and aluminum silicate. The latter compound has been identified as an amorphous phase of sillimanite, from the following facts: It shows no crystalline form, has an index of refraction above 1.60, and by heating at a higher temperature (about 1450°) it inverts to minute needle crystallites corresponding to sillimanite in all determinable optical properties.

Up to 1340° in mixtures of quartz and feldspar the quartz dissolves to only a small extent in the feldspar glass. At 1460° the quartz is practically completely dissolved in specimens having as high a quartz content as 50 per cent quartz to 50 per cent feldspar.

At 1340° in specimens containing kaolin and feldspar the kaolin dissociates entirely. The amount of crystallized and amorphous sillimanite increases with an increased content of kaolin, at least to a concentration of 50 per cent kaolin to 50 per cent feldspar.

At 1460° 10 per cent kaolin is apparently entirely soluble in the feldspar glass. With higher concentrations of kaolin the amount of crystallized sillimanite increases. The needle crystals are well developed and comparatively large.

At 1310° in quartz-clay-feldspar bodies the feldspar is present as a glass; the clay shows almost complete dissociation, with the formation of amorphous sillimanite mainly and but little crystallized sillimanite, while the quartz is undissolved and the grains may possess considerable size, up to 0.2 mm.

By burning these bodies at 1380° to 1400° the feldspar glass dissolves considerable quartz, there being only a comparatively small amount of quartz remaining. The quartz grains are much rounded and etched, and they seldom have a length of 0.06 mm. The clay is dissociated with the formation of crystallized sillimanite, although an extremely small amount of amorphous sillimanite may be present.

The changes involved by burning commercial bodies are identical with those of laboratory-prepared bodies. Commercial ware ranges from a low-burned porous whiteware, in which, except for the dehydration of the clay, only the feldspar is changed, to high-fired chemical porcelain, which consists of glass, sillimanite crystallites, and more or less of residual quartz. The quartz grains observed in the whiteware and in the low-fired vitreous ware are large and angular, sometimes having a length of 0.2 mm or more, whereas in the hard porcelains, due to solution, the quartz grains are rounded, etched, and seldom exceed 0.05 mm in length.

The constitution and the microstructure of porcelain depend upon the temperature of burning, and change as this temperature changes. Their variation with temperature is given in Table 4. This table has served as the basis for the prediction of the probable burning temperatures of the commercial bodies, which was accomplished with success. It appears that the time-of-burning factor is by no means as important as the burning temperature in determining the constitution and microstructure of the ware.

Mention must be made here that no cristobalite or tridymite has been definitely observed in any of the laboratory or commercial bodies examined. It appears that the quartz dissolves in the feldspar glass more readily than it inverts to the other modifications.

In conclusion, we may state that the petrographic microscopic study of porcelain led to interesting and, it is to be hoped, important technical results. It has placed the chemical and physical processes involved in the formation of porcelain on a more quantitative thermal basis. Furthermore, it has offered a means of estimating the burning temperature of a ware from the examination of a fragment much too small in size to be satisfactory for even a chemical analysis.

Acknowledgments are due to Prof. A. V. Bleininger for his kindly suggestions throughout the work; to H. A. Brady for the preparation of the thin sections; and to W. L. Howat, C. S. Kinnison, and P. Teetor for the preparation of the bodies examined.

WASHINGTON, July 7, 1916.

TABLE 1

Analyses of Materials Used in the Preparation of Feldspar-Quartz-Clay Specimens [a]

	North Carolina kaolin	Tennessee ball clay	Georgia kaolin	Feldspar	Quartz
	Per cent	Per cent	Per cent	Per cent	Per cent
Silica	45.84	50.80	45.69	70.79	99.23
Alumina	38.46	32.09	37.52	16.75	.32
Ferric oxide	.57	1.56	.53	.22	.10
Titanium oxide	.11	1.23	1.61	....	....
Calcium oxide	.19	.18	.18	.24	.08
Magnesium oxide	.08	.40	.25	.18	.13
Sodium oxide	.07	.38	.11	3.29	....
Potassium oxide	.35	1.14	.20	8.26	....
Loss on ignition	14.44	12.49	14.05	.46	.22
Total	100.11	100.27	100.14	100.19	100.08

[a] In the feldspar-quartz-clay specimens, the clay material was introduced as North Carolina kaolin, Tennessee ball clay, and Georgia kaolin in the proportions of 5:1:1.

TABLE 2

Porcelain Series I

[These analyses were calculated to a water-free basis from the analyses of the raw materials.]

Specimen No.	Clay	Feldspar	Quartz	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	CaO	MgO	Na_2O	K_2O
	Per ct.	Per ct.	Per ct.	Per ct.	Per ct.	Per ct.	Per ct.	Per ct.	Per ct.	Per ct.	Per ct.
1	35	10	55	82.04	15.71	0.36	0.18	0.14	0.15	0.39	1.02
2	35	13	52	81.13	16.23	.36	.18	.15	.15	.49	1.28
3	35	16	49	80.24	16.74	.37	.18	.16	.15	.60	1.55
4	35	19	46	79.34	17.26	.37	.18	.17	.15	.69	1.81
5	40	10	50	79.87	17.79	.39	.20	.15	.15	.40	1.06
6	40	13	47	78.96	18.31	.40	.20	.16	.15	.50	1.33
7	40	16	44	78.05	18.83	.40	.20	.17	.16	.61	1.59
8	40	19	41	77.14	19.35	.40	.20	.17	.15	.71	1.86
9	40	22	38	76.24	19.88	.41	.20	.17	.16	.82	2.12
10	40	25	35	75.34	20.40	.41	.20	.18	.17	.92	2.39
11	45	10	45	77.63	19.88	.43	.24	.16	.16	.41	1.09
12	45	13	42	76.73	20.41	.43	.24	.16	.15	.51	1.36
13	45	16	39	75.82	20.93	.44	.24	.17	.16	.62	1.62
14	45	19	36	74.90	21.46	.44	.24	.18	.16	.72	1.89
15	45	22	33	73.99	22.00	.44	.24	.18	.16	.82	2.16
16	45	25	30	73.08	22.52	.45	.24	.18	.17	.93	2.43
17	50	19	31	72.65	23.63	.47	.26	.17	.15	.73	1.93
18	50	22	28	71.72	24.16	.48	.26	.17	.15	.84	2.20

TABLE 3

Porcelain Series II

[These analyses were calculated to a water-free basis from the analyses of the raw materials]

Specimen No.	Clay	Feld-spar	Quartz	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	CaO	MgO	Na_2O	K_2O
	Per ct.	Per ct.	Per ct.	Per ct.	Per ct.	Per ct.	Per ct.	Per ct.	Per ct.	Per ct.	Per ct.
1	35	30	35	76.15	19.16	0.38	0.18	0.18	0.16	1.10	2.77
2	35	40	25	73.08	20.93	.39	.18	.20	.16	1.43	3.65
3	35	50	15	70.08	22.63	.41	.18	.21	.17	1.78	4.50
4	35	60	5	67.07	24.36	.42	.18	.22	.18	2.18	5.38
5	35	65	....	65.55	25.22	.42	.18	.24	.18	2.30	5.81
6	40	40	20	70.81	23.01	.43	.20	.21	.17	1.45	3.70
7	45	30	25	71.56	23.42	.45	.24	.19	.16	1.11	2.87
8	45	35	20	70.13	24.31	.46	.24	.20	.17	1.28	3.31
9	45	40	15	68.60	25.17	.47	.24	.21	.17	1.47	3.75
10	45	55	....	64.08	27.82	.48	.24	.24	.18	1.99	5.08
11	50	30	20	69.28	25.56	.50	.26	.19	.16	1.13	2.91
12	50	40	10	66.20	27.34	.50	.26	.22	.16	1.49	3.81
13	50	50	....	63.15	29.12	.52	.26	.23	.17	1.84	4.68

TABLE 4

Temperature of Porcelain Burning as Indicated by the Constitution and Microstructure of the Burned Specimens

Observations on constitution and microstructure	Probable burning temperature
Feldspar melted to a glass; no apparent dissociation of dehydrated kaolin; no solution of quartz	About 1200°
Feldspar melted; slight dissociation of dehydrated clay with the formation of amorphous sillimanite; no solution of quartz	About, 1225°
Feldspar melted; increase in dissociation of dehydrated clay with the formation of amorphous sillimanite; no solution of quartz	About 1250°
Feldspar melted; considerable dissociation of dehydrated clay with the formation of amorphous sillimanite and a trace of crystallized sillimanite; no solution of quartz	About 1275°
Feldspar melted; almost complete dissociation of dehydrated clay but the amount of sillimanite crystals still very small; practically no solution of quartz	About 1300°
Feldspar melted; complete dissociation of dehydrated clay with a small increase in the amount of sillimanite crystals although amorphous sillimanite still predominates; beginning of quartz solution	About 1325°
Feldspar melted; sillimanite needles appear to be almost as plentiful as amorphous sillimanite; solution of quartz is still comparatively small although noticeably greater than at 1325°	About 1350°
Feldspar melted; amount of sillimanite needles greater than that of amorphous sillimanite; quartz dissolved to quite an extent	About 1375°
Feldspar melted; dissociation product of dehydrated clay consists almost entirely of crystallized sillimanite; quartz considerably dissolved	About 1400°
Feldspar melted; comparatively little undissolved quartz; porcelain consists almost almost entirely of glass and sillimanite needle crystals	About 1425° or more